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Correlation of Coal Properties with
Environmental Control Technology Needs for
Sulfur and Trace Elements

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FINAL REPORT

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ABSTRACT

This report reviews existing reports and data on the occurrence of sulfur and trace elements in U.S. coals and on the effect of coal properties on trace element partitioning during coal utilization. Areas of emphasis include 1) the effect of depositional conditions on the formation and composition of mineral matter in coal, 2) the elemental concentration of major and trace elements in U.S. coals as a function on rank and geographic location, 3) analytical methods used for evaluating the modes of occurrence of these elements in coal, 4) conceptual models for predicting sulfur and trace element occurrence as a function of depositional conditions and chemical equilibrium, and 5) the fate of major and trace elements during coal cleaning, combustion, gasification, and waste disposal.

Coal washability data for 44 U.S. coal samples were used to statistically estimate the trace element reduction potential for a coal as a function of sulfur and ash reduction. Data fits were especially good for elements associated with the clay minerals, and to a lesser extent with the sulfides. Analysis of coal combustion data from 15 previous studies at commercial power plants was also conducted, but due to differences in technological processes at various plants, possible analytical errors, and limited data, statistical correlations are uncertain. Areas identified for future research into elemental partitioning as a function of coal properties include development of further information on the effect of depositional conditions on coal quality, extension of the coal washability data base to additional coals (including analysis of mineral forms in these coals), and collection and analysis of additional data on the partitioning of trace elements during combustion.

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SECTION 1

INTRODUCTION

1.1 BACKGROUND

Of the 92 naturally occurring elements (excluding the transuranic elements), all but 16 have been detected in coal. As analytical detection levels are further improved and as additional coals are examined, the number of elements found in coal may increase. However, except for the elements forming the organic structure of coal (hydrogen, carbon, oxygen, sulfur, and nitrogen) and the associated major ash forming elements (aluminum, calcium, iron, magnesium, phosphorus, potassium, silicon, sodium, and titanium), the concentrations of other elements are almost universally less than 0.1 percent and are commonly referred to as "trace elements."¹ Of these trace elements, antimony, arsenic, boron, cadmium, germanium, mercury, molybdenum, and selenium are commonly found in concentrations greater than typically found in the earth's crust. For certain locations and ranks of coal, lead and zinc are also found in concentrations greater than the earth's crustal average. Table 1 summarizes the average enrichment factors for selected elements in U.S. coals relative to the average concentration in the earth's crust.

During coal mining, preparation, transportation, and utilization, trace elements may be released into the environment and potentially affect occupational and public health. The exact pathways and magnitudes of human exposure to coal-related trace element releases are not known. However, based on

¹Elements in coal are frequently divided into three groups based on their concentration: major (>10 percent), minor (0.1-10 percent), and trace (<0.1 percent). However, the usefulness of these terms and their definitional boundaries is limited. This report uses only two groups: major elements (consisting of the ten elements constituting 99+ percent of the mineral matter in essentially all coals and included in ASTM procedures for determining major ash oxides) and trace elements (consisting of all other ash-forming elements and which are generally present in coals at concentrations less than 0.1 percent).

TABLE 1. AVERAGE ENRICHMENT FACTORS OF TRACE ELEMENTS IN COAL
RELATIVE TO THE AVERAGE COMPOSITION OF THE EARTH'S CRUST.

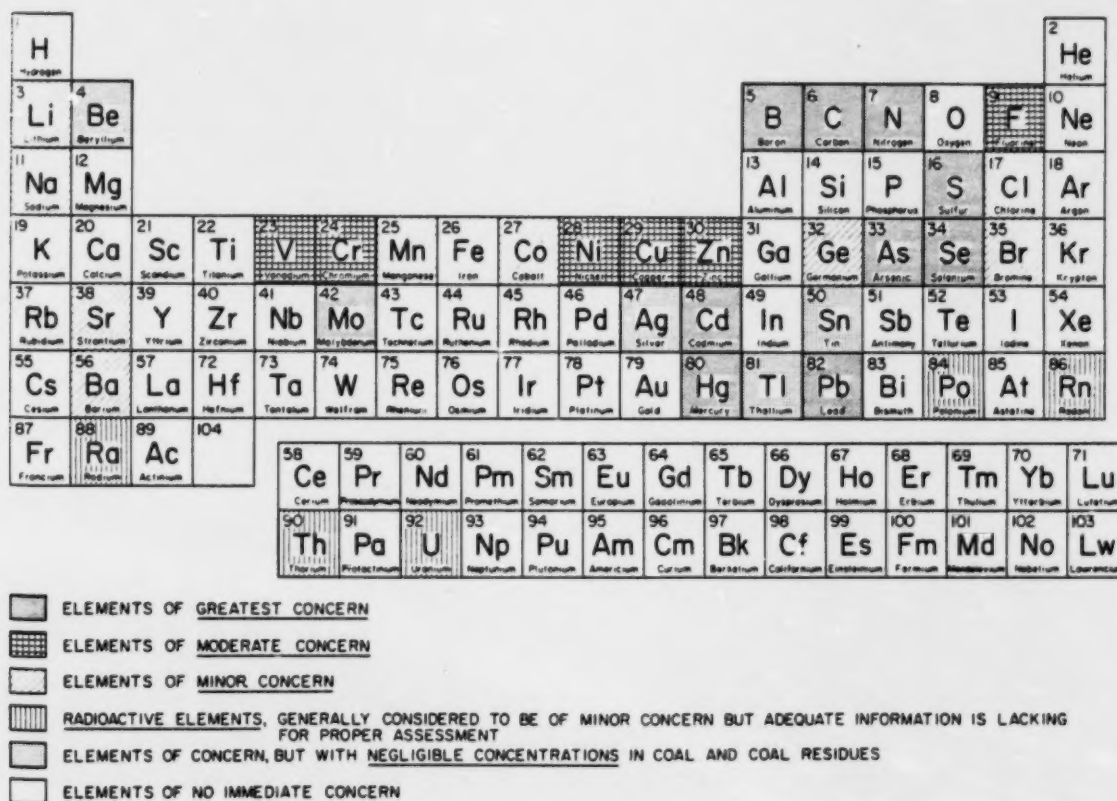
Limited Enrichment (1-3)		Moderate Enrichment (3-10)		Significant Enrichment (>10)	
Element	Enrichment	Element	Enrichment	Element	Enrichment
Lead	1.04	Antimony	5.80	Arsenic	10.2
Mercury	2.38	Boron	4.30	Selenium	61.4
Molybdenum	2.15	Cadmium	4.35		
Zinc	1.11	Germanium	4.23		

Source: References 1 and 2.

available data on trace element releases and known health impacts from trace element exposure, the National Research Council (3)² has identified seven trace elements (arsenic, boron, cadmium, lead, mercury, molybdenum, and selenium) plus certain compounds of carbon, nitrogen, and sulfur as being of greatest concern to public health. As shown in Figure 1, the NRC also identified other trace elements associated with coal as being of moderate, minor, unknown, and negligible concern. The gaseous oxide emissions of carbon and nitrogen, although major environmental concerns, are not examined by this report. Table 2 summarizes the major environmental impacts associated with the remaining elements of major concern.

Given this general background on the occurrence of the sulfur and trace elements in coal and the potential public health concerns associated with these emissions, what is the potential for predicting sulfur and trace element releases from a specific coal having certain measureable properties? How are these emissions affected by the design of processing technology and environmental control systems? And, to what extent can the magnitude of environmental impacts associated with the use of a specific coal be estimated?

²References indicated by use of parentheses are listed at the end of each section.



Source: Reference 3

Figure 1. Potentially Hazardous Elements in Coal Resources Development

TABLE 2. ENVIRONMENTAL IMPACTS ASSOCIATED WITH SULFUR AND MAJOR TRACE ELEMENTS

Element	Impacts
Sulfur [Sulfur dioxide (SO ₂), sulfates (SO ₄), sulfuric acid (H ₂ SO ₄)]	Decreased pulmonary function; increased acidity of rainfall and surface waters; damage to property and biological systems
Arsenic	Toxic at elevated levels to most biological systems through accumulation in tissue
Boron	Toxic at elevated levels to plant systems
Cadmium	Similar to arsenic
Lead	Similar to arsenic
Mercury	Similar to arsenic
Molybdenum	Uptake in plants dangerous to foraging livestock and wildlife
Selenium	Similar to molybdenum

1.2 OVERVIEW OF THIS REPORT

The objectives of this report are to review:

- the occurrence of sulfur and trace elements in coal;
- the status of existing knowledge related to the release of sulfur and trace elements into the atmosphere during coal preparation, combustion, conversion to synthetic fuels, and disposal of solid wastes;
- methodologies for the evaluation of sulfur and trace element partitioning and environmental release potential as a function of (1) the original coal properties and (2) the utilization and environmental control technologies; and

- the extent of data gaps and potential research needs associated with the fate of coal-derived trace elements and sulfur compounds during utilization.

The report is subdivided into four sections corresponding to each of the above objectives. Section 2 reviews the chemical, petrographic, and mineralogical properties of coal related to the occurrence of sulfur and trace elements. A summary of existing and ongoing research in these areas as well as the availability of basic data on coal composition through the U.S. Geological Survey's National Coal Resource Data System (NCRDS) and Pennsylvania State University's Coal Data Base are also presented.

Section 3 discusses the status of existing knowledge regarding the release of sulfur and trace elements during coal preparation, combustion, synthetic fuels production, and solid waste disposal. The primary focus of this section is on:

- the relative size of potential pollutant streams,
- the partitioning of trace elements and sulfur compounds between these streams during processing,
- the importance of coal properties on this partitioning,
- the environmental significance of pollutant emissions from these activities and process streams, and
- areas where analysis of existing data or conduct of additional research is needed.

The development of methodologies for estimating the partitioning of sulfur and trace elements during coal cleaning, combustion, and solid waste disposal are presented in Section 4. These methodologies are based on previous research programs conducted by a number of different groups and on a statistical analysis of sulfur and trace element data contained in NCRDS. In order

to further test the suggested methodologies, selected data are also used from the Penn State Coal Data Base and other sources.

Section 5 provides a summary of existing knowledge on the importance of coal properties on process technology selection, environmental control technology requirements, and sulfur and trace element emissions. Finally, the report identifies existing data gaps and future research needs.

1.3 REFERENCES

1. U.S. Geological Survey (1982) National Coal Resources Data System, USCHEM File, averages for 4,402 channel samples of U.S. coals.
2. Taylor, S. R. (1964) "Abundance of Elements in the Continental Crust—A New Table," Geochim. Cosmochim. Acta, Vol. 28, pp. 1273-1285.
3. National Research Council (1980) Trace Element Geochemistry of Coal Resource Development Related to Environmental Quality and Health, National Academy Press, Washington, DC, 153 pp.

SECTION 2

COAL CHARACTERISTICS, AS RELATED TO SULFUR AND TRACE ELEMENTS

Understanding the fate of sulfur and trace elements in coal necessitates an awareness of the complexity of coal's structure and composition. Resulting from the sedimentary accumulation of peat in ancient bogs and gradual diagenesis, coal is a highly heterogeneous rock composed predominately of complex organic molecules and lesser amounts of minerals, water, and gases. The organic molecules in the coal are derived from the tissue and exudate of plant matter and as a group are referred to as "macerals." The minerals consist of a variety of clays, silicates, carbonates, sulfates, sulfides, phosphates, oxides, hydroxides, and salts. Trace elements occur in association with the minerals and, to a lesser extent, the macerals.

This section is divided into three major parts. Section 2.1 reviews the process by which peat is converted into coal and characterizes the major maceral and mineral groups. Section 2.2 provides background on the occurrence of sulfur and trace elements in U.S. coals as a function of rank and location. The association of sulfur and trace elements with the organic and inorganic fractions in coal are discussed in Section 2.3. Appendix I reviews the two major computerized data sources documenting sulfur and trace element occurrence in coals—the U.S.G.S. National Coal Resource Data System (NCRDS) USCHEM file and the Pennsylvania State University Coal Data Base.

2.1 COAL FORMATION AND COMPOSITION

Coal can be subdivided into three fractions: organic matter consisting primarily of hydrogen, carbon, oxygen, and nitrogen; moisture; and inorganic matter consisting of everything else. Proximate and ultimate analyses obtained from the pyrolysis and oxidation of coal are based on this division. In the coal itself, however, the clear separation of material into these three groups is not always possible.

2.1.1 The Process of Coal Formation

Coal is formed through the progressive metamorphism of plant matter accumulated in ancient bogs. Conversion of plant matter into coal is controlled by a number of interrelated factors and results in the development of economically important coal deposits only when the proper conditions exist. These interrelated factors include plant species,¹ climate, topography, hydrology, fresh-water/marine influences, plant nutrient supply, bacterial activity, reduction-oxidation (redox) potential, and post-depositional conditions. A simplified discussion of the process of "coalification" focusing on the sources of sulfur and trace elements in coal is presented below. A more detailed discussion is presented in Chapters 2 and 3 of Stach's Textbook of Coal Petrology (1) and in Chapter 2 of the Chemistry of Coal Utilization (2).

2.1.1.1 Peatification

Two stages exist in the coalification process. The first stage consists of the accumulation of plant matter in stagnant swamps and bogs and the alteration of this matter by bacteria. This process of peat diagenesis is commonly referred to as "peatification," "biochemical coalification," or "first-stage coalification." During peatification, oxygen-rich substances in the plant matter (e.g., cellulose, starch, and proteins) are decomposed by bacteria and fungi into gaseous and liquid products which escape from the area of generation. The remaining humic substances (primarily humic acid) plus the bacteria-resistant, carbon-rich lignins in the original peat are the major source of organic matter in coal. The carbon content of the bog on a dry, mineral matter free basis increases from 45-50 percent in the unaltered plant

¹The two major coal types—humic coals and sapropelic coals—are differentiated based on the predominant source of the original organic matter. Humic coals are formed primarily from humic materials of decomposed cellular plants and are the predominant type of coal found in the U.S. Sapropelic coals are the result of spore and algae accumulations in deep waters and are much less common. The descriptions of coal formation processes and compositions presented herein are based on humic coals.

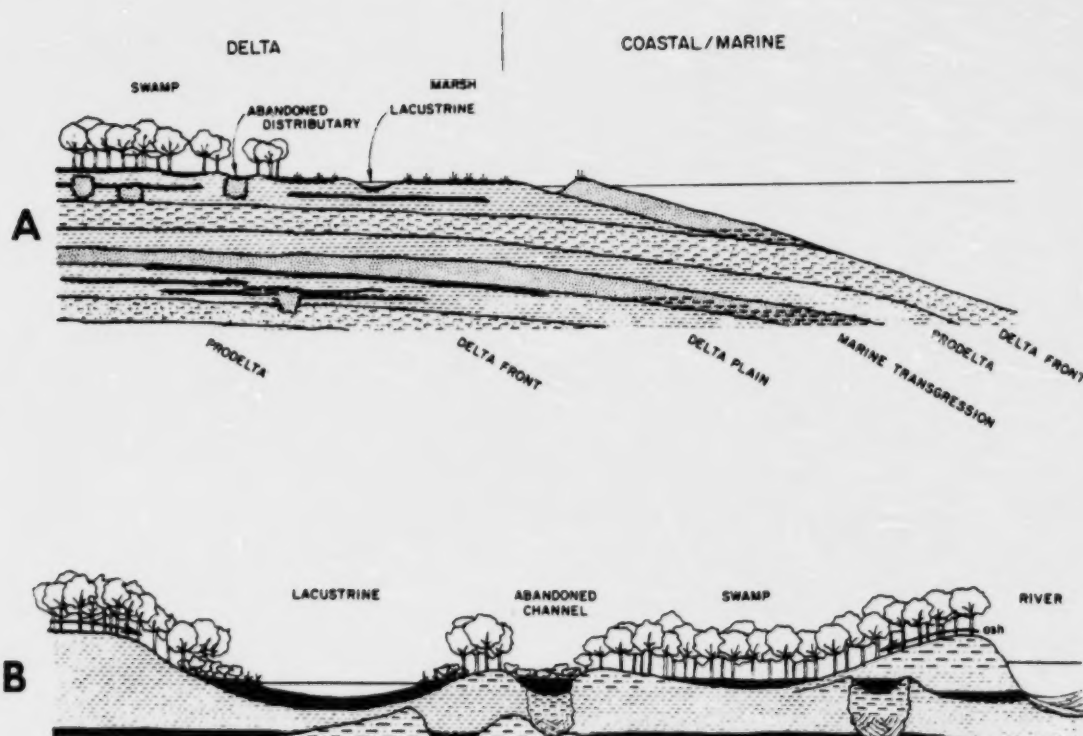
matter to 55-60 percent in the reduced peat. At the same time burial and compaction of the bog results in the reduction of moisture content.

2.1.1.1.1 Depositional Environments

Thick deposits of peat can develop under two basic sets of conditions. In the first instance, referred to as "low moors," peat accumulates in swamps formed in topographic depressions (such as those associated with ox-bow lakes, areas of rapid subsidence, or coastal swamps protected from destruction by barrier islands). Fluvial, deltaic, and coastal/marine depositional environments (3,4) are all examples of low-moor systems. Schematic cross-sections of these low-moor coal-forming environments are shown in Figure 2. Fluvial and upper deltaic systems are generally characterized as fresh water systems whereas systems in lower deltaic and coastal areas exhibit increased marine influence. Coals found in interchannel basins formed by alluvial ridges of ancient fluvial and upper deltaic systems tend to have lesser amounts of detrital material in the coal than in the coals of lower deltaic and coastal origin. The modern peats developing along the coast of the Carolinas and in the Mississippi River delta are examples of low-moor environments. Low-moor coals can include terrestrial plants (e.g., conifer trees) as well as aquatic plants (e.g., cypress and water lilies).

The second environment of deposition is found in humid areas where the annual rainfall exceeds the rate of evaporation and is referred to as "high-moors." In high moors, peat accumulates on relatively flat to slightly convex surfaces as a result of plant matter growing and being deposited within the bog. High-moor deposits are generally not a significant source of U.S. coals. The best modern example of a high-moor, coal-forming environment occurs on several islands of Indonesia.

In most commercial coal deposits, the precursor plant matter is formed in place from plants living within the swamp or bog and results in "autochthonous" coals. These coals are relatively free of detrital mineral matter and other materials washed into the area during ancient floodings. In contrast, "allochthonous" coals are the result of plant matter which was transported



Source: Reference 3

Figure 2. Schematic Cross Section of Various Environments of Coal Formation in Delta/Coastal-Marine Systems (A) and a Fluvial System (B)

into a topographic depression. Allochthonous coals usually contain high concentrations of mineral matter and are generally not of economic value for this reason. A third type of plant accumulation results in "hypoautochthonous" coals which form from frequent flooding of a swamp and rearrangement of the organic materials already in the swamp. These coals are characterized by a higher content of detrital matter than in autochthonous coals. The detritus generally consists of finely-divided shells, calcareous algae, animal skeletons, and silt and occurs both as fine layers in the coal and as dispersed material.

2.1.1.1.2 Depositional Chemistry

Water is an essential element in the formation of peat swamps or bogs and in the ultimate composition of the coal. First, in order for the plant matter to be preserved, oxygen must be rapidly reduced or excluded from contact with the plant matter in order to prevent complete decomposition of the material. For this reason, coal-forming environments are generally associated with stagnant, anaerobic swamps and areas where the water table is at or very near the surface of the bog.

Second, the source and abundance of water will influence the acidity of the swamp or bog which in turn affects bacterial activity, the fixation of sulfur compounds, and the fixation of trace elements. Several studies have concluded that marine-influenced coal swamps exhibit neutral to slightly alkaline conditions (pH 7.0-8.0) which are favorable for sulfur fixation by bacteria (6, 7). Chou (7) in a study of the Illinois No. 6 seam concluded that coals overlain by marine sediments had appreciably higher levels of S, Fe, B, Hg, Mo, Tl, V, and W than coals associated with freshwater sediments.

In contrast to the generally accepted importance of marine influence on acidity and sulfur levels, Cecil et al. (8) contend that the general paleoclimate, and specifically the ratio of rainfall versus evaporation, is of primary importance. During periods in which rainfall exceeds evaporation, acidic swamp conditions develop due to the washing of alkaline materials out of the

swamp. Under these conditions, coals will be low in ash and sulfur. Conversely, in periods of increased evaporation, sediments can become highly alkaline with resultant coals exhibiting high levels of ash and sulfur. Cecil et al. (9) further discuss the importance of alkaline sediments (specifically calcium carbonate) in the peat development process by comparing the Upper Freeport, Pocahontas No. 3, and Vermillion Creek coals (all of freshwater origin but with differing levels of calcium carbonate) with Lower Kittanning coal which was subjected to post-depositional marine conditions. The postulated role of paleoclimate and associated rock types on the sulfur contents in these coals appears to correlate with the data in Table 3.

TABLE 3. COMPARISON OF DEPOSITIONAL SETTING VS.
TOTAL SULFUR CONTENT IN FOUR U.S. COALS

Seam	Depositional Setting	No. of Samples	Average Sulfur (%)	Standard Deviation (%)
Lower Kittanning	total	255	2.64	1.16
	marine	71	3.15	1.17
	transitional	48	2.45	1.03
	nonmarine	125	1.73	0.81
Upper Freeport	nonmarine	183	2.09	0.85
Pocahontas No. 3	nonmarine	43	0.67	0.31
Vermillion Creek Wyoming	nonmarine		4-8	

Source: Reference 9.

The pH of fresh-water, low-moor swamps is generally 4.5-6.5 while raised bogs or high moors which occur only in regions of high rainfall have a pH of 3.5-4.5. Little bacterial activity occurs to decompose the plant matter at these lower pH levels, resulting in significant preservation of the original plant structure in the coal and reduced levels of sulfur fixation. most conversion is by chemical reactions. The sphagnum peats familiar to gardeners are produced in these raised bog, highly acid environments.

The third water-related impact on coal quality is the extent and diversity of plant nutrient supply present in the associated surface and ground waters. Under equal hydrologic conditions, the vegetation will be more luxuriant and diverse in species in nutrient rich (eutrophic) swamps than in nutrient poor (oligotrophic) swamps. High-moor peats dependent primarily on rainfall contain roughly one-fifth the nutrients (calcium, phosphoric acid, potash, nitrogen, and various trace elements) of low-moor peats which receive dissolved nutrients from surface water inflows. Nutrients may also be infused into the bog (primarily at its lower levels) by uptake of nutrients by plant roots extending into underlying strata.

2.1.1.2 Coalification

The second stage in the formation of coal is referred to as "geochemical coalification" (as opposed to biochemical coalification), "second-stage coalification," or simply "coalification." The boundary between peatification and coalification is based on the loss of bacterial activity (both aerobic and anaerobic) and accompanying changes in the composition of the strata as shown in Table 4. Changes in the coal during the coalification stage include chemical and physical alterations resulting from time, temperature, and pressure. The major changes in coals during coalification occur in specific sequences.

TABLE 4. DISTINCTION BETWEEN PEAT AND LIGNITE

	Peat	Lignite
Moisture	>75%	<75%
Carbon (daf*)	usually <60%	usually >60%
Free Cellulose	Yes	No

*daf = dry, ash-free basis.

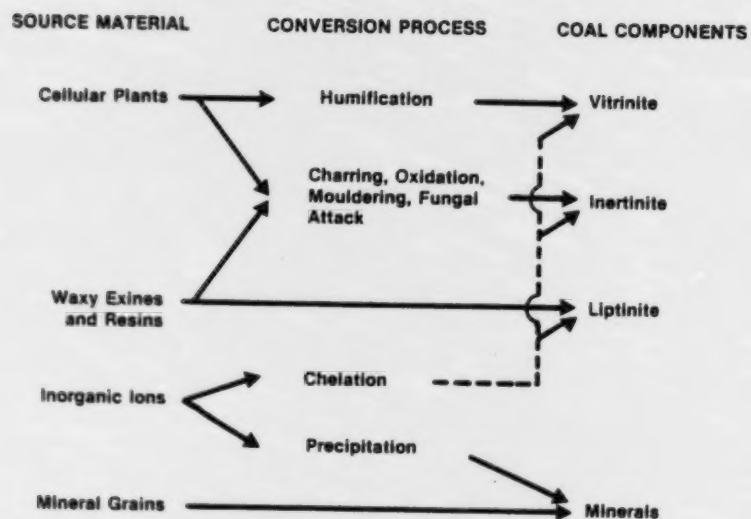
Source: Reference 1, p. 38.

The first major change is associated with the continued compaction of the bed, loss of porosity, and decrease in moisture content during the transition from lignite to bituminous coal. Associated with this loss in moisture content is the loss of hydrophylic functional groups, such as hydroxyl ($-\text{OH}$), carboxyl ($-\text{COOH}$), methoxyl ($-\text{OCH}_3$), and carbonyl ($>\text{C}=\text{H}$). The loss of these functional groups is significant in two regards. First, it results in a loss of oxygen and further increase in carbon content in the coal. Second, and of greater importance to this study, the loss of these organic functional groups reduces the number of sites within the coal molecule suitable for inorganic ion exchange and chelation. In the lower rank coals, carboxyl groups tie up a significant portion of the major and minor elements as carboxylate salts (10). The conversion of lignite to subbituminous coal is also marked by the transformation of remnant lignin and cellulose into humic materials and the conversion of humic materials into larger molecules of alkali-insoluble humins.

In the bituminous coal range, there is further reduction in the moisture content and a loss of volatile carbon compounds. The loss of volatile compounds results from the loss of aliphatic and alicyclic groups from the coal and the increased aromatization of the humic compounds. In the latter stages of bituminous coal (when carbon content has reached roughly 87 percent and volatile content has fallen below 29 percent), additional changes result in the prolific generation of methane gas. The generation of methane further lowers the hydrogen/carbon ratio in the coal and results in the development of anthracite.

2.1.2 Macerals and Minerals

The above section on coalification discusses two of the important methods of characterizing the composition of coals—elemental content and molecular structure. A third method is the description of organic and inorganic components. As opposed to a coal's elemental and molecular composition which are strongly influenced by the coalification process, the maceral and mineral components are related primarily to the original material deposited in the peat bog plus the inorganic precipitates from associated waters. As shown in Figure 3, the origin of the macerals and minerals in the coal can be generally



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Source: Modified from Reference 2

Figure 3. Relationship Between Original Source Material and Coal Macerals/Minerals

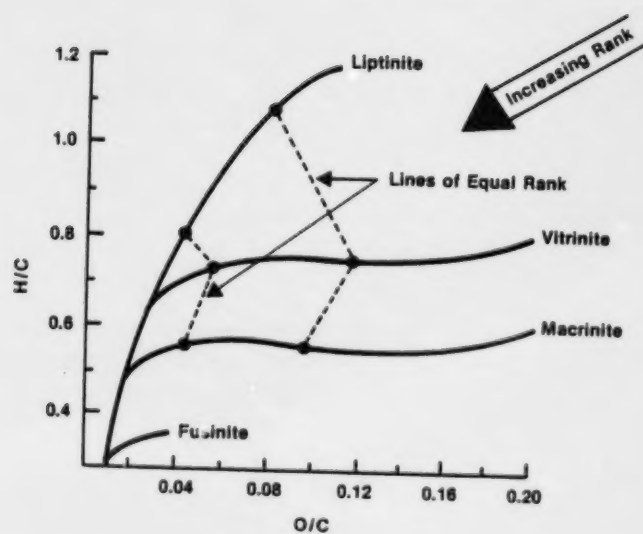
identified. The specific source of these members is not easily established in many cases however (e.g., whether specific components are the result of mineral uptake by plants from underlying sediments or the result of detrital influx into the bog or swamp).

2.1.2.1 Macerals

Macerals comprise the organic matter in coal and are directly related to the original plant material deposited in the bog or swamp. The major mechanisms for inclusion of sulfur and trace elements in the organic structure of coal are through uptake of nutrients in bottom sediments or other sources by the peat-forming plants, and through binding of inorganic ions as chelates or adsorbed cations (11). Also, while strictly not a part of the organic structure, finely divided mineral grains can be trapped within the maceral structure and appear in some technological applications to be associated with the organic constituents in the coal.

Three basic categories of macerals are recognized: vitrinite, liptinite (also known by the name "exinite"), and inertinite. Because of the differences in the original plant matter forming the macerals, each responds differently to the coalification process. As an example, Figure 4 illustrates the variations in the hydrogen/carbon versus oxygen/carbon ratio signatures for each maceral; coal rank is a function of the degree of coalification of each maceral (macrinite and fusinite are specific macerals in the inertinite group). These three maceral groups occur in individual coals in varying ratios. Depending on which maceral is most abundant, its amount relative to the other macerals, and the degree of metamorphism, coals can be subdivided into various lithotypes. Coal petrology is the branch of coal science involved with the study of macerals.

While substantial information on the origin and composition of coal is obtained from analysis of the macerals, to date the practical application of this information has been limited to better understanding the behavior of coals for coke production and liquefaction. Only limited knowledge exists on



9-82-10497

Source: Reference 2

Figure 4. Coalification Tracks of Various Macerals Based on H/C and O/C Ratios

the relationship between specific macerals and the occurrence of trace elements and sulfur in coals. However, due to the belief held by many coal scientists that coal petrology may some day yield additional insight into the technological characteristics and environmental implications of specific coals, a brief review of each of the three major maceral groups is provided below.

2.1.2.1.1 Vitrinite

Vitrinites are the coalification products of humic substances derived from lignin and cellulose in trees and other cellular plants. North American coals are predominantly (75-80 percent) vitrinite.⁴

The two major processes in vitrinite formation from the original peat are "humification" and "gelification." Humification involves the slow oxidation of the original plant matter to form humic acids of varying molecular weights and solubilities. Lignin- and tannin-rich cell walls of tree roots, woods, and barks are relatively resistant to this decomposition process and retain their physical identity in coal. The cellulose-rich leaves and twigs are more readily decomposed and converted into a colloidal solution of humic detritus which permeates the unconverted plant materials. In the presence of appropriate cations (e.g., Na, Ca, Mg, and Al), humic acids are transformed into humate salts. During the loss of water through burial, heating, and compaction, the colloidal humic solution is precipitated as a very finely divided gel. During the change of lignite into subbituminous coal, the undecomposed plant cells and the humic gel are converted to vitrinite.

The chemical properties of vitrinite are affected more strongly and uniformly during the bituminous coal and anthracite stages of coalification than are liptinite and inertinite. As a result, vitrinites are frequently

⁴Technically vitrinites do not occur in lignites, but are produced beginning at the subbituminous stage from humic material present in lignite. In lignite, these vitrinite precursors are called huminite.

used to determine coal rank. During bituminous and anthracite stages, four coalification jumps occur at the high-volatile bituminous stage, the medium-volatile bituminous stage, the boundary between semi-anthracite and anthracite, and at the anthracite/meta-anthracite boundary. The major changes in the vitrinite macerals during this sequence are the decrease in oxygen, hydrogen, and volatile matter and the enrichment of carbon. Because the volatile constituents in coal consist of aliphatic and alicyclic compounds, the increase in rank of vitrinite is also accompanied by an increase in aromaticity.

2.1.2.1.2 Liptinite

Liptinite (also referred to as "exinite") is formed from the coalification of plant materials containing substantial amounts of fatty substances. The principal sources of these materials are spores, pollens, cutin, suberin, resins, waxes, balsams, latex, fats, and oils produced by plants as well as certain bacterial products resulting from carbohydrate degradation. Relative to the humic materials which form vitrinite, these fatty substances are rich in hydrogen, contain large amounts of aliphatic compounds, and are highly resistant to humification and gelification.

Due to their resistance to biological and chemical attack, liptinite materials remain largely unaffected by metamorphic changes through the sub-bituminous rank. At the boundary between subbituminous and bituminous, it is believed that carboxyl radicals are freed and reduction processes occur, resulting in the formation of a petroleum-like substance. At the transition from high-volatile to low-volatile bituminous, a second shift or jump occurs associated with the destruction of these petroleum-like substances to form gaseous hydrogen and volatile matter. Beyond this point the liptinite macerals become indistinguishable from the vitrinite.

2.1.2.1.3 Inertinite

The inertinite maceral group consists of a variety of individual macerals primarily formed through the "fusinitization" of humic materials prior to humification. Fusinitization involves various processes such as charring,

oxidation, mouldering, and fungal attack which produce substances high in carbon content and low in hydrogen. Some inertinites also appear to form as secondary macerals (i.e., by-products) from the coalification of liptinitic constituents.

The fusinitization process (e.g., the burning of trees by fire prior to their deposition in the swamp or the attack of wood by dry rot) produces a "precoalified" material which is relatively unaffected by the coalification process except for the loss of oxygen and, at the bituminous rank and above, the loss of residual hydrogen. The term "inertinite" was selected to describe the relatively stable composition of the fusinized materials during the production of coke. However, in other technological processes (e.g., liquefaction), certain inertinites may be reactive.

2.1.2.1.4 Lithotypes and Microlithotypes

Coals are a composite of the above macerals and minerals. A nomenclature has been established to describe various combinations of macerals, both as seen by the unaided eye (lithotypes) and as seen through a microscope (microlithotypes).

Microlithotypes are divided into three major groups (monomacerals, bimacerals, and trimacerals) based on the number of macerals required in a sample to constitute at least 95 percent of the total; a fourth group (carbo-minerite) is used to describe coals containing in excess of 20 percent mineral matter. To distinguish the microlithotypes from the macerals in the nomenclature, the suffix "-ite" is used in place of the "-inite" of the macerals. The specific names are shown in Table 5.

Lithotypes are used to differentiate macroscopic bands found in a coal seam based on the relative brightness and texture of the band. Four lithotypes are recognized: vitrain, clarain, durain, and fusain. Vitrain, as the name suggests, consists primarily of vitrinite and is visually distinguished by its brightness. Durain corresponds to the microlithotype durite as well as

TABLE 5. CLASSIFICATION OF MICROLITHOTYPES

Microolithotype	Maceral	Volume %
Monomaceralic		
Vitrite	Vitrinite (V)	>95%
Liptite	Liptinite (L)	>95%
Inertite	Inertinite (I)	>95%
Bimaceralic		
Clarite	V + L	>95%
Vitrinertite	V + I	>95%
Durite	I + L	>95%
Trimaceralic		
Duroclarite	V + I + L	V > (I + L)
Clarodurite	V + I + L	I > (L + V)
Vitrinertoliptite	V + I + L	L > (I + V)
Carbominerite	V, L, I and mineral matter (MM)	20% < MM < 60%

Source: Reference 2, p. 127.

to other vitrinite poor bands in a coal seam. Because of the absence of vitrinite, durain has a dull appearance. To be classified as vitrain or durain, the band must exceed one centimeter in thickness. The most abundant lithotype is clarain which is semi-bright in appearance and is characterized by multiple thin bands (less than one centimeter) composed of various microolithotypes including vitrite, clarite, durite, fusite, and trimacerite. Fusain has a silky luster and usually is found in lenses in the coal bed rather than as continuous bands. Fusain lenses are usually concentrated at a certain horizon in a coal seam corresponding to a fire or other fusinization event.

2.1.2.2 Minerals

In addition to the organic macerals in coal, over 125 separate minerals have been identified in coal (12).⁵ In 1935 V.M. Goldshmidt (13) proposed three general pathways for accumulation of mineral matter in coal.

⁵Appendix II of Ref. 12 provides a detailed bibliography on the individual minerals in coal.

1. Accumulation in the plant during its growth,
2. Concentration during the decay of organic plant materials, and
3. Concentration after burial.

Goldshmidt attributed observed concentrations of vanadium, molybdenum, and nickel to the existence of organometallic complexes in coal. Goldshmidt (14) also concluded that certain elements associated with the inorganic fraction would tend to form sulfides (the chalcophile elements—As, Cd, Co, Cu, Ni, Pb, Zn, Sb, Hg, and Fe) while others would be more common as clays and silicates (the lithophile elements—Si, Al, Mg, Ti, and K).

Cecil et al. (15) divide Goldshmidt's three sources of minerals into five more specific processes:

1. Accumulation in the plant during its growth,
2. Detrital minerals washed or blown into the peat-forming environment (including volcanic sources),
3. Sorption of soluble ions from associated water sources on the surface of peat particles,
4. Precipitation by chemical and/or biochemical processes during peat accumulation, and
5. Precipitation by chemical processes during subsequent stages of coalification.

Minerals resulting from materials introduced into the bog or swamp at the time of peat accumulation are generally referred to as "syngenetic" minerals and include Cecil's first four processes of mineral origin discussed above.

Minerals precipitated in cracks, fissures, and other voids in the coal matrix after peat burial are identified as "epigenetic" minerals. The syngenetic minerals are further subdivided into two groups: "authigenic" minerals formed from materials originally in the peat or formed in-place by precipitation or other chemical/biological processes, and "detrital" minerals consisting of solids transported into the peat by water and wind. An alternative method of differentiating minerals is to distinguish minerals easily separated from the organic structure of coal ("extraneous" or "adventitious" minerals) from those too closely associated with the organic matrix to be readily separated ("inherent" minerals). While epigenetic minerals are generally large sized and thus readily separable (i.e., extraneous), precise and unequivocal distinctions between authigenic vs. detrital or extraneous vs. inherent—although potentially of substantial scientific and technological importance—are not always possible.

The quantitative significance of each of these sources of mineral matter, specifically the significance of detrital sources, is a topic of current debate among coal scientists. Two basic lines of reasoning currently exist. The more widely held position is that detrital sources account for a significant portion of the mineral matter in many coals. Finkelman (16) has suggested that based on textural, mineralogical, and chemical evidence, mineral matter in bituminous coals with less than roughly five percent ash⁶ is attributable to authigenic minerals formed from materials present in the original plant; at ash levels above five percent, detrital sources play an increasingly significant role. Cecil and Stanton (18) dispute the criteria used in making this division and believe that substantially higher levels of authigenic ash can be obtained through loss of organic matter in strongly degraded peats.

The four major mineral groups (clays, carbonates, sulfides, and silicates) are discussed below. Lesser mineral groups include sulfates, phosphates, oxides, hydroxides, and salts. These less abundant mineral groups are of minor quantitative importance in most coals and are not further discussed

⁶For lignites, an ash level of 8 percent is suggested (17).

in this report. The associations of trace elements with the various organic and mineral groups are identified on Table 6 and are discussed further in Section 2.3.

2.1.2.2.1 Clay Minerals

The clay minerals (also referred to as "aluminosilicates") constitute the largest single mineral group in most coals, ranging from 40 to 80 percent of the total inorganic fraction. The most common clays are illite, kaolinite, and mixed-layer clays consisting of illite and montmorillonite. While the genesis of these minerals in coal is not fully understood, they are found as finely divided grains (grain diameters are generally less than several microns) mixed with the coal and as horizontally banded kaolinite-rich claystones interbedded with the coal. The fine-grained clays are generally believed to form by precipitation of matter originally in the plants and from detrital sources. Based on textural and maceral relationships, Finkelman (16) suggests that kaolinite is of predominantly authigenic origin and the illite and montmorillonite are primarily detrital. Cecil et al. (15) however, believe that all of the clay minerals may be formed authigenically.

Relative to the other minerals in coal, the abundance of clay minerals has the least variability (i.e., smallest standard deviation relative to mean value). This reflects the large amount of authigenic clay contributed to coal from plant sources as well as the impact detrital materials can have on the swamp environment. Carbonaceous rocks with high levels of clay are classified as carbonaceous shales rather than coal.

The horizontal claystone bands, referred to as "tonsteins," are generally believed to result from deposition of volcanic ash, but may also be attributable to more recent events (1). Minerals frequently present in tonsteins include kaolinite, large quartz grains, apatite, zircon, and various titanium oxides (12). Because of their considerable lateral continuity, tonsteins are useful in stratigraphic correlation of coal seams.

TABLE 6. PRINCIPAL MINERALS FOUND IN COAL AND TRACE CONSTITUENTS

Mineral Phases	Major Constituents	Abundance ¹	Trace Constituents ²
Clay minerals			
Kaolinite	Al, Si	5-30%	Ti, Mg, Fe, and others
Illite	Al, Si, K	30->60%	Fe, Mg, Ca, Na, K, Ti,
Montmorillonite	Al, Si, Mg, Fe	1-10%	Li, V, B, Mn, Cr, Cu, Ni,
Chlorite	Al, Si, Mg	1-5%	Rb, Cs, Ga, Be, Zn, Se, F, La, Ba, Sr, Co, and others
Sulfides			
Pyrite, Marcasite	Fe, S	1-10%	As, Cd, Hg, Ag, Pb,
Sphalerite	Zn, S	1-5%	Fe, Zn, Cu, Co, Sn,
Galena	Pb, S	1-5%	Ni, Mo, Se, Ga
Chalcopyrite	Cu, Fe, S	<1%	
Carbonates			
Calcite	Ca	5-30%	Ba, Sr, Pb, Mn, Ca
Siderite	Fe	5-30%	Fe, Mg
Ankerite	Ca, Fe	5-30%	
Dolomite	Ca, Mg	1-10%	
Silicates			
Quartz	Si	1-10%	
Zircon	Si, Zr	1-5%	Hf, Th, P
Tourmaline	Ca, Mg, Fe, B, Al, Si	<1%	Li, F
Plagioclase feldspar	Ca, Na, Al, Si	ND ³	Ba, Sr, Mn, Ti, Fe, Mg
Alkali feldspar	K, Na, Al, Si	ND ³	Rb, Ba, Sr, Fe, Mg, Ti, Li
Muscovite	K, Na, Al, Si	ND ³	F, Rb, Cs, Ba, Mg, Fe
Sulfates			
Barite	Ba, S	1-5%	
Gypsum	Ca, S	1-5%	Sr, Pb, Ca
Phosphates			
Apatite	Ca, P, F	1-5%	Rare earths, U, Cs, Mn, Cl, Mg
Oxides and Hydroxides			
Limonite, Goethite	Fe	1-10%	ND ³
Diaspore	Al	1-5%	ND ³
Hematite, Magnetite	Fe	<1-5%	ND ³
Rutile	Ti	<1%	ND ³
Salts			
Halite	Na, Cl	<1-10%	ND ³
Sylvite	K, Cl	<1-10%	ND ³
Bischofite	Mg, Cl	<1-10%	ND ³

¹Reference 1, p. 155, percentage of the mineral matter.²Reference 19, p. 59, listing of mineral/trace elements is representative and does not preclude other possible associations.³No data provided in cited publications.

The clay minerals, especially illite and montmorillonite, are of significant technological importance to coal preparation processes because of their swelling tendencies in the presence of water (and thus the lowering of their specific gravity). The clay minerals also are of importance to trace element analyses because of their cation exchange capacity, particularly in lignite and subbituminous coal.

2.1.2.2.2 Carbonate Minerals

The second largest mineral group in most coals is the carbonates. Siderite and dolomite formation are associated with peatification: siderite forms in peats of fresh-water origin and dolomite forms in marine-influenced environments. Calcite and ankerite are commonly found in cracks and fissures and are therefore considered to be primarily associated with second-stage coalification.

2.1.2.2.3 Sulfides

From an environmental standpoint, sulfide minerals are of special importance because of their conversion to sulfur dioxide during combustion and to hydrogen sulfide during reduction processes. Principal among the sulfide minerals are the two polymorphs of iron disulfide (FeS_2): pyrite and marcasite. Sphalerite (ZnS), galena (PbS), and chalcopyrite (CuFeS_2) are also common. Arsenic and mercury are found in coal primarily in association with pyrite, while cadmium is associated almost entirely with sphalerite.

Fine-grained sulfides are usually formed by syngenetic processes associated with the bacterial conversion of sulfates to sulfur. Coarse-grained sulfide complexes of pyrite, sphalerite, galena, and sometimes chalcopyrite are associated with both syngenetic and epigenetic precipitation processes. Reaction of siderite [iron carbonate (FeCO_3)] with hydrogen sulfide (H_2S) can also produce pyrites.

Due to the chemical similarity of sulfur and selenium (both are Group VI elements in the periodic table and have a valance of -2), certain chalcophile elements, particularly lead, may also occur as selenides. The occurrence of lead selenide is especially common in the Appalachian region, but has also been found elsewhere (12). Lead selenide generally appears as a coprecipitate with sphalerite, and to a lesser extent with chalcopyrite.

Due to the number of variables influencing the formation of various sulfide minerals in coal (pH of the swamp, availability of individual chalcophile elements, epigenetic precipitation in fissures), the frequency of occurrence of sulfides in coal is highly variable. Within individual coals, pyrite levels range from less than 0.1 percent to over 3.0 percent on an as-received, whole coal basis.

2.1.2.2.4 Silicates

Quartz (SiO_2) is the dominant silicate mineral in coal. Quartz grains found in coal can result from both authigenic precipitation of pore fluids and from fine-grained detritus carried by water and wind. Detrital quartz is a significant constituent of clay tonsteins. With the possible exception of feldspars, the other silicates found in coal are generally too rare to be of significance.

2.2 OCCURRENCE OF TRACE ELEMENTS IN U.S. COALS

The first major studies quantifying the occurrence of trace elements in U.S. coals were those of Zubovic, Stadnichenko, and Sheffey at the U.S. Geological Survey (20-23) and of Abernathy and Gibson at the U.S. Bureau of Mines (24). Zubovic et al., analyzed coals from the Northern Great Plains (20), Eastern Interior (21), Appalachian (22), and Western Interior (23) regions for 15 elements (B, Be, Cr, Co, Cu, Ga, Ge, La, Mo, Ni, Sn, Ti, V, Y and Zn). Gibson and Abernathy analyzed 827 coal samples taken from existing mines for the ten major inorganic elements plus 34 trace elements (24). In addition,

Abernathy and Gibson provide citations to almost 400 previous studies on trace elements (many focused on a single element) and compare trace element contents of U.S. coals with those found in coals from other countries.⁷

While these studies provide a valuable general data base of trace element information, caution should be exercised in using the concentrations reported in these studies (and in many of the earlier studies) due to the limitations of semiquantitative spectrochemical and colorimetric procedures then available (25, 26). Because of the inherent analytical imprecision of these methods, values reported in these early reports may be in error by several hundred percent. Also of concern in many of these earlier studies is the failure to accurately account for the loss of volatile trace elements (e.g., As and Hg) during the process of ashing coal samples prior to analysis.

Since the late 1960s significant advances have been made in instrumental methods for analyzing trace elements and have substantially reduced the sources of variation in sample analysis. Gluskoter et al. (26) and NRC (27) overview and provide citations to relevant literature regarding modern techniques and their comparative accuracy. In addition, Analytical Chemistry (28) provides an annual review of current procedures.

The most extensive published source of trace element data was produced by Swanson et al. (29) of the USGS in 1976. This report contains data for 799 coal samples taken from 150 producing mines and includes the most important U.S. coal seams. Summary tables were produced to reflect average trace element contents for coals in each of the seven major coal provinces and by rank. Sample descriptions are provided on a state-by-state basis for 15 of the nation's coal regions. Data used in this study became the initial input into the USCHEM file of the USGS National Coal Resources Data System (NCRDS) (see Appendix I).

⁷More recent bibliographies on trace elements in coal are provided in References 25-27.

As part of the current study, trace element statistics were tabulated by rank and province for the 4,402 channel samples in the NCRDS as of November 1982 (Tables 7 and 8, respectively). Statistics were also prepared for six subgroups of bituminous coals (Table 9). These six subgroups represent the Pottsville and Monongahela Groups, and Allegheny Formation of the Appalachian Region, the eastern and western regions of the Interior Province, and the Rocky Mountain Province. As can be seen from these data, significant variations are present in the trace element contents of U.S. coals, both by rank and by geographic area.

The far right column of Table 7 is the average value of each element in the earth's crust (known as "clarkes"). Despite large standard deviations which may approach or exceed the average coal values for many of the elements in Table 7, all major and most trace element concentrations in most coals are less than the elements' clarkes values. Antimony, arsenic, boron, cadmium, germanium, mercury, molybdenum, and selenium, and in some ranks and locations lead, silver, and zinc, are enriched relative to average crustal concentrations. If an enrichment ratio of ten is used to indicate substantial enrichment of trace elements, only arsenic and selenium are of concern.

Several trends in these data are noteworthy. First, calcium, magnesium, sodium, boron, germanium, and strontium occur at increased concentrations in low-rank coals; these elements generally believed to be bound as exchangeable cations to the organic matter and clays in low-rank coals. Second, the average concentration of several chalcophiles (Fe, As, Cd, Ni, and Zn) and sulfur are greater in the Interior Province and the Monongahela and Allegheny formations of the Appalachian Province than elsewhere in the country. In some instances, enrichment may be at least partially attributable to regional geochemical conditions. For example, zinc enrichment in coals of the Interior Province may be related to mineral deposits with high zinc concentrations that occur in this area. A third apparent trend is the increased levels of several diverse elements (Ga, La, Sc, Se, Th, V, Yb, Y, and Zr) in Gulf Coast lignites.

TABLE 7. SULFUR, ASH, AND TRACE ELEMENTS IN U.S. COALS BY RANK^a

	Units	Anthracite	Bituminous	Subbituminous	Lignite	Clarke ^b
Number of samples		52	3527	640	183	
Sulfur (S), total	%	0.86 ±0.80	2.31 ±2.08	0.59 ±0.67	1.08 ±1.01	0.026
Sulfur (S), sulfate	%	0.02 ±0.02	0.14 ±0.27	0.05 ±0.10	0.22 ±0.67	—
Sulfur (S), pyritic	%	0.37 ±0.78	1.50 ±1.82	0.19 ±0.41	0.36 ±0.64	—
Sulfur (S), organic	%	0.49 ±0.16	0.92 ±0.63	0.37 ±0.30	0.57 ±0.38	—
Ash	%	15.0 ±8.94	12.6 ±9.26	14.0 ±23.7	21.5 ±22.9	—
Silicon (Si)	%	6.56 ±1.41	5.25 ±1.51	5.21 ±2.11	6.73 ±4.62	28.15
Aluminum (Al)	%	4.73 ±0.77	2.87 ±0.92	2.47 ±0.85	2.77 ±1.46	8.23
Calcium (Ca)	%	0.20 ±0.24	0.42 ±0.59	1.72 ±1.16	3.31 ±2.28	4.15
Magnesium (Mg)	%	0.15 ±0.21	0.11 ±0.10	0.42 ±0.33	1.01 ±0.74	2.33
Sodium (Na)	%	0.07 ±0.13	0.06 ±0.07	0.25 ±0.33	0.37 ±0.53	2.36
Potassium (K)	%	0.30 ±0.13	0.22 ±0.97	0.10 ±0.09	0.19 ±0.24	2.09
Iron (Fe)	%	0.87 ±0.85	2.37 ±1.86	0.95 ±0.92	1.51 ±1.41	5.63
Manganese (Mn)	%	0.01 ±0.02	0.01 ±0.01	0.01 ±0.02	0.03 ±0.02	0.10
Titanium (Ti)	%	0.29 ±0.11	0.14 ±0.07	0.13 ±0.06	0.20 ±0.12	0.57
Phosphorus (P)	%	0.07 ±0.10	0.05 ±0.09	0.13 ±0.14	0.18 ±0.28	0.11
Antimony (Sb)	ppm	1.12 ±1.84	1.22 ±2.27	0.85 ±1.40	1.01 ±2.23	0.2
Arsenic (As)	ppm	7.67 ±19.6	20.3 ±41.8	6.17 ±15.5	22.8 ±138	1.8
Barium (Ba)	ppm	102 ±61.7	84.4 ±132	447 ±924	415 ±531	425
Beryllium (Be)	ppm	1.32 ±0.85	2.22 ±1.66	1.30 ±1.77	1.98 ±2.71	2.8
Boron (B)	ppm	11.8 ±10.5	37.6 ±41.7	52.6 ±38.5	114 ±75.2	10
Cadmium (Cd)	ppm	0.22 ±0.30	0.91 ±7.30	0.38 ±0.47	0.55 ±0.61	0.2
Chromium (Cr)	ppm	47.2 ±60.9	20.5 ±27.5	14.9 ±25.6	13.5 ±18.2	100
Cobalt (Co)	ppm	7.27 ±9.42	9.74 ±24.5	6.63 ±18.3	6.46 ±15.1	25
Copper (Cu)	ppm	18.9 ±16.4	17.8 ±17.8	14.1 ±14.3	17.2 ±21.2	55
Fluorine (F)	ppm	103 ±93.5	88.5 ±103	83.0 ±92.7	191 ±360	625
Gallium (Ga)	ppm	6.26 ±3.82	5.99 ±4.42	4.97 ±5.76	6.64 ±8.66	15
Germanium (Ge)	ppm	1.71 ±2.17	6.33 ±10.2	5.93 ±6.55	10.7 ±11.1	1.5

(Continued)

TABLE 7. (Continued)

	Units	Anthracite	Bituminous	Subbituminous	Lignite	Clarks ^b
Lanthanum (La)	ppm	14.0 $\pm$ 7.88	10.7 $\pm$ 8.32	13.0 $\pm$ 12.2	20.5 $\pm$ 23.7	30
Lead (Pb)	ppm	7.32 $\pm$ 6.92	14.3 $\pm$ 27.5	6.35 $\pm$ 5.47	6.90 $\pm$ 7.88	12.5
Lithium (Li)	ppm	26.0 $\pm$ 28.9	10.3 $\pm$ 26.3	9.24 $\pm$ 11.9	11.6 $\pm$ 18.5	20
Mercury (Hg)	ppm	0.23 $\pm$ 0.27	0.21 $\pm$ 0.42	0.10 $\pm$ 0.11	0.15 $\pm$ 0.14	0.08
Molybdenum (Mo)	ppm	2.68 $\pm$ 2.44	3.28 $\pm$ 4.13	2.19 $\pm$ 2.82	5.99 $\pm$ 26.3	1.5
Nickel (Ni)	ppm	28.5 $\pm$ 32.0	16.9 $\pm$ 19.2	7.02 $\pm$ 8.44	8.35 $\pm$ 19.7	75
Scandium (Sc)	ppm	6.04 $\pm$ 5.85	3.79 $\pm$ 2.73	2.84 $\pm$ 2.84	4.64 $\pm$ 4.73	22
Selenium (Se)	ppm	3.11 $\pm$ 2.58	3.39 $\pm$ 4.00	1.44 $\pm$ 1.42	2.70 $\pm$ 3.67	0.05
Silver (Ag)	ppm	0.13 $\pm$ 0.10	0.08 $\pm$ 0.15	0.61 $\pm$ 1.54	0.20 $\pm$ 0.07	0.07
Strontium (Sr)	ppm	73.7 $\pm$ 77.0	88.1 $\pm$ 95.0	171 $\pm$ 184	309 $\pm$ 258	375
Thorium (Th)	ppm	6.09 $\pm$ 2.92	3.03 $\pm$ 3.15	5.13 $\pm$ 4.64	7.13 $\pm$ 5.70	9.6
Uranium (U)	ppm	1.94 $\pm$ 3.38	1.85 $\pm$ 2.71	2.13 $\pm$ 3.84	3.39 $\pm$ 10.3	2.7
Vanadium (V)	ppm	37.8 $\pm$ 33.1	22.3 $\pm$ 19.7	23.9 $\pm$ 30.6	29.1 $\pm$ 37.3	135
Ytterbium (Yb)	ppm	1.00 $\pm$ 0.67	0.94 $\pm$ 0.65	0.77 $\pm$ 0.85	1.43 $\pm$ 1.92	3
Yttrium (Y)	ppm	10.3 $\pm$ 5.24	8.35 $\pm$ 6.36	7.73 $\pm$ 7.97	12.8 $\pm$ 16.5	33
Zinc (Zn)	ppm	12.6 $\pm$ 14.5	92.4 $\pm$ 689	17.4 $\pm$ 21.1	22.5 $\pm$ 79.8	70
Zirconium (Zr)	ppm	39.1 $\pm$ 23.6	24.7 $\pm$ 26.5	25.7 $\pm$ 27.4	42.1 $\pm$ 62.1	165

^aWhole-coal basis; mean $\pm$ standard deviation.^bAverage elemental concentration in crustal rocks, Reference 2, Section 1.

TABLE 8. SULFUR, ASH, AND TRACE ELEMENTS IN U.S. COALS BY PROVINCE^a

	Units	Appalachian	Interior	Gulf	Northern Great Plains	Rocky Mountain	Alaska
No. of Samples		2749	592	38	371	512	107
Sulfur (S), total	%	2.13 ±1.90	3.83 ±2.42	0.88 ±0.42	0.83 ±0.88	0.58 ±0.47	0.44 ±0.79
Sulfur (S), sulfate	%	0.08 ±0.18	0.39 ±0.40	0.09 ±0.14	0.07 ±0.14	0.03 ±0.07	0.02 ±0.01
Sulfur (S), pyritic	%	1.45 ±1.75	2.12 ±2.05	0.14 ±0.14	0.38 ±0.69	0.12 ±0.15	0.09 ±0.14
Sulfur (S), organic	%	0.84 ±0.58	1.33 ±0.68	0.74 ±0.26	0.43 ±0.38	0.42 ±0.20	0.30 ±0.28
Ash	%	12.5 ±9.50	12.8 ±7.27	17.9 ±10.5	11.4 ±12.5	16.6 ±16.0	15.5 ±12.5
Silicon (Si)	%	5.46 ±1.33	4.06 ±1.57	7.07 ±2.63	3.03 ±1.60	7.57 ±2.37	5.75 ±2.08
Aluminum (Al)	%	3.10 ±0.76	1.89 ±0.87	3.31 ±0.98	1.51 ±0.56	3.26 ±1.14	3.13 ±0.90
Calcium (Ca)	%	0.26 ±0.30	0.88 ±0.90	1.56 ±1.00	2.01 ±0.97	1.45 ±1.21	1.86 ±1.22
Magnesium (Mg)	%	0.10 ±0.06	0.12 ±0.13	0.37 ±0.23	0.57 ±0.32	0.31 ±0.28	0.42 ±0.26
Sodium (Na)	%	0.06 ±0.05	0.06 ±0.07	0.06 ±0.05	0.32 ±0.35	0.15 ±0.19	0.20 ±0.24
Potassium (K)	%	0.24 ±0.12	0.19 ±0.09	0.09 ±0.08	0.06 ±0.06	0.11 ±0.11	0.22 ±0.17
Iron (Fe)	%	2.24 ±1.79	3.49 ±1.89	1.13 ±1.07	0.89 ±0.92	0.99 ±0.76	0.91 ±0.54
Manganese (Mn)	%	0.01 ±0.01	0.01 ±0.03	0.03 ±0.01	0.01 ±0.01	0.01 ±0.02	0.02 ±0.02
Titanium (Ti)	%	0.15 ±0.06	0.09 ±0.04	0.25 ±0.11	0.10 ±0.05	0.16 ±0.06	0.18 ±0.14
Phosphorus (P)	%	0.04 ±0.07	0.05 ±0.07	0.03 ±0.01	0.10 ±0.11	0.18 ±0.23	0.22 ±0.20
Antimony (Sb)	ppm	1.19 ±2.34	1.58 ±2.20	1.05 ±0.86	0.55 ±0.71	0.79 ±1.47	1.24 ±1.39
Arsenic (As)	ppm	22.2 ±45.5	16.3 ±23.0	4.74 ±3.53	6.33 ±15.8	4.72 ±12.3	5.25 ±4.45
Barium (Ba)	ppm	74.5 ±66.6	70.0 ±232	161 ±132	443 ±427	353 ±1019	534 ±292
Beryllium (Be)	ppm	2.27 ±1.68	2.29 ±1.60	2.08 ±2.85	1.23 ±1.86	1.37 ±1.72	0.78 ±0.74
Boron (B)	ppm	29.1 ±31.1	78.1 ±60.4	151 ±85.6	70.5 ±54.0	60.1 ±48.6	39.7 ±31.1
Cadmium (Cd)	ppm	0.13 ±0.21	5.47 ±18.5	0.50 ±0.49	0.30 ±0.48	0.35 ±0.39	0.28 ±0.59
Chromium (Cr)	ppm	18.2 ±13.6	27.2 ±54.1	21.2 ±10.9	7.53 ±12.9	19.7 ±27.4	39.7 ±46.9
Cobalt (Co)	ppm	7.52 ±19.7	16.7 ±37.8	5.57 ±6.02	3.13 ±5.17	11.1 ±23.8	19.1 ±29.8
Copper (Cu)	ppm	18.2 ±18.2	17.5 ±14.6	26.5 ±16.1	9.82 ±10.2	13.8 ±16.0	20.1 ±16.6
Fluorine (F)	ppm	89.9 ±108	77.4 ±74.6	67.8 ±50.4	76.2 ±123	123 ±205	84.4 ±72.9
Gallium (Ga)	ppm	6.27 ±4.56	4.99 ±3.45	9.52 ±5.57	3.37 ±5.22	5.95 ±6.50	5.15 ±4.76
Germanium (Ge)	ppm	3.98 ±6.30	17.1 ±16.1	7.81 ±7.75	4.89 ±3.79	7.11 ±8.60	6.24 ±6.05

(Continued)

TABLE 8. (Continued)

	Units	Appalachian	Interior	Gulf	Northern Great Plains	Rocky Mountain	Alaska
Lanthanum (La)	ppm	10.8 $\pm$ 8.0	10.2 $\pm$ 11.7	36.4 $\pm$ 27.9	10.7 $\pm$ 10.6	13.8 $\pm$ 13.1	12.7 $\pm$ 8.3
Lead (Pb)	ppm	8.93 $\pm$ 9.42	10.5 $\pm$ 18.9	14.4 $\pm$ 13.0	6.39 $\pm$ 10.1	11.8 $\pm$ 12.8	13.7 $\pm$ 24.1
Mercury (Hg)	ppm	0.24 $\pm$ 0.47	0.14 $\pm$ 0.14	0.24 $\pm$ 0.19	0.11 $\pm$ 0.10	0.09 $\pm$ 0.12	0.08 $\pm$ 0.07
Molybdenum (Mo)	ppm	3.03 $\pm$ 3.51	4.97 $\pm$ 6.15	3.24 $\pm$ 2.04	2.70 $\pm$ 15.3	2.09 $\pm$ 2.53	2.75 $\pm$ 4.66
Nickel (Ni)	ppm	15.4 $\pm$ 14.7	26.7 $\pm$ 32.6	14.0 $\pm$ 13.0	5.33 $\pm$ 9.67	6.71 $\pm$ 8.19	11.2 $\pm$ 8.8
Scandium (Sc)	ppm	4.00 $\pm$ 2.77	3.09 $\pm$ 2.42	6.58 $\pm$ 2.54	2.06 $\pm$ 2.27	2.96 $\pm$ 2.88	4.57 $\pm$ 3.56
Selenium (Se)	ppm	3.56 $\pm$ 4.03	3.37 $\pm$ 4.33	8.14 $\pm$ 3.49	0.98 $\pm$ 1.25	1.73 $\pm$ 1.20	0.96 $\pm$ 1.43
Silver (Ag)	ppm	0.06 $\pm$ 0.06	0.20 $\pm$ 0.32	0.18 $\pm$ 0.07	0.32 $\pm$ 0.24	1.02 $\pm$ 1.45	0.90 $\pm$ 2.18
Strontium (Sr)	ppm	93.2 $\pm$ 92.3	44.0 $\pm$ 78.6	119 $\pm$ 113	242 $\pm$ 196	154 $\pm$ 208	169 $\pm$ 103
Thorium (Th)	ppm	2.98 $\pm$ 2.33	3.73 $\pm$ 6.60	8.96 $\pm$ 6.33	4.30 $\pm$ 3.74	5.13 $\pm$ 4.65	3.49 $\pm$ 2.54
Uranium (U)	ppm	1.66 $\pm$ 1.87	2.98 $\pm$ 5.07	3.07 $\pm$ 2.64	1.59 $\pm$ 2.24	2.40 $\pm$ 4.40	1.28 $\pm$ 1.43
Vanadium (V)	ppm	22.4 $\pm$ 18.0	22.8 $\pm$ 22.2	48.8 $\pm$ 25.8	14.8 $\pm$ 26.9	20.7 $\pm$ 23.3	50.3 $\pm$ 47.1
Ytterbium (Yb)	ppm	0.96 $\pm$ 0.63	0.83 $\pm$ 0.80	1.67 $\pm$ 0.94	0.61 $\pm$ 0.97	0.89 $\pm$ 1.09	0.98 $\pm$ 0.79
Yttrium (Y)	ppm	8.22 $\pm$ 5.83	8.76 $\pm$ 7.87	16.2 $\pm$ 11.1	6.07 $\pm$ 8.37	9.41 $\pm$ 10.2	8.95 $\pm$ 6.99
Zinc (Zn)	ppm	22.9 $\pm$ 43.6	442 $\pm$ 1638	18.7 $\pm$ 32.3	15.9 $\pm$ 20.7	16.0 $\pm$ 21.1	17.5 $\pm$ 24.4
Zirconium (Zr)	ppm	25.6 $\pm$ 27.7	18.5 $\pm$ 17.9	49.3 $\pm$ 46.0	17.7 $\pm$ 23.7	34.9 $\pm$ 40.8	29.0 $\pm$ 27.5

^aWhole-coal basis; mean $\pm$ standard deviation.

TABLE 9. SULFUR, ASH, AND TRACE ELEMENTS IN U.S. BITUMINOUS COAL BY FORMATION/REGION*

No. of Samples	Units	Pottsville Group	Allegheny Formation	Monongahela Formation	Illinois Basin	Western Interior	Rocky Mountain
		1111	1005	341	275	305	184
Sulfur (S), total	%	1.19 ±0.96	2.64 ±2.28	3.09 ±1.38	3.21 ±1.53	4.40 ±2.85	0.66 ±0.61
Sulfur (S), sulfate	%	0.04 ±0.07	0.11 ±0.23	0.10 ±0.13	0.33 ±0.32	0.45 ±0.44	0.03 ±0.04
Sulfur (S), pyritic	%	0.64 ±0.87	1.80 ±2.13	1.89 ±1.15	1.48 ±1.15	2.66 ±2.45	0.12 ±0.17
Sulfur (S), organic	%	0.65 ±0.28	0.88 ±0.69	1.21 ±0.60	1.41 ±0.70	1.28 ±0.70	0.47 ±0.19
Ash	%	9.39 ±6.72	14.7 ±11.8	12.9 ±6.74	10.9 ±5.76	14.3 ±7.27	11.8 ±7.17
Silicon (Si)	%	4.34 ±0.95	6.13 ±1.58	5.41 ±1.26	4.13 ±1.18	3.72 ±1.53	5.34 ±1.47
Aluminum (Al)	%	2.51 ±0.52	3.57 ±0.88	2.67 ±0.56	1.94 ±0.64	1.69 ±0.89	2.32 ±0.81
Calcium (Ca)	%	0.21 ±0.23	0.30 ±0.34	0.32 ±0.37	0.46 ±0.52	1.35 ±1.12	1.09 ±0.84
Magnesium (Mg)	%	0.09 ±0.04	0.10 ±0.04	0.11 ±0.11	0.08 ±0.03	0.17 ±0.20	0.20 ±0.16
Sodium (Na)	%	0.06 ±0.05	0.05 ±0.04	0.05 ±0.03	0.06 ±0.06	0.05 ±0.06	0.13 ±0.16
Potassium (K)	%	0.19 ±0.10	0.28 ±0.14	0.23 ±0.08	0.18 ±0.08	0.19 ±0.09	0.07 ±0.06
Iron (Fe)	%	1.15 ±1.07	3.18 ±2.24	3.10 ±1.50	2.65 ±1.59	4.35 ±2.06	0.68 ±0.45
Manganese (Mn)	%	0.01 ±0.01	0.01 ±0.01	0.01 ±0.01	0.01 ±0.01	0.02 ±0.05	0.01 ±0.01
Titanium (Ti)	%	0.13 ±0.05	0.17 ±0.07	0.13 ±0.03	0.09 ±0.03	0.08 ±0.04	0.11 ±0.05
Phosphorus (P)	%	0.03 ±0.06	0.05 ±0.09	0.05 ±0.06	0.03 ±0.05	0.10 ±0.08	0.14 ±0.17
Antimony (Sb)	ppm	1.19 ±1.59	1.44 ±3.28	0.58 ±0.56	1.29 ±1.55	1.87 ±2.68	0.43 ±0.71
Arsenic (As)	ppm	16.7 ±29.9	29.2 ±63.9	20.7 ±28.7	11.9 ±13.6	20.3 ±28.9	1.82 ±5.08
Barium (Ba)	ppm	85.8 ±73.5	61.2 ±59.3	66.9 ±50.0	73.7 ±242	67.1 ±225	183 ±156
Beryllium (Be)	ppm	2.49 ±2.02	2.33 ±1.44	1.51 ±0.98	2.82 ±1.66	1.78 ±1.29	0.95 ±0.85
Boron (B)	ppm	18.9 ±17.7	31.0 ±33.2	50.1 ±29.4	123 ±56.4	66.6 ±56.1	64.1 ±56.4
Cadmium (Cd)	ppm	0.11 ±0.12	0.15 ±0.20	0.10 ±0.13	1.35 ±7.17	11.8 ±26.8	0.18 ±0.15
Chromium (Cr)	ppm	14.2 ±10.6	21.1 ±14.5	16.6 ±10.3	15.2 ±16.3	36.9 ±70.8	25.7 ±37.1
Cobalt (Co)	ppm	7.07 ±4.88	7.69 ±11.8	4.53 ±5.29	5.89 ±5.37	25.1 ±47.2	14.8 ±22.2
Copper (Cu)	ppm	21.1 ±17.2	19.2 ±20.7	8.41 ±11.0	12.9 ±10.1	21.4 ±16.4	8.54 ±5.60
Fluorine (F)	ppm	80.1 ±119	97.9 ±106	93.6 ±101	67.8 ±49.9	75.9 ±55.7	102 ±109
Gallium (Ga)	ppm	5.16 ±3.88	7.38 ±5.09	5.13 ±3.30	4.43 ±2.43	5.55 ±3.75	4.21 ±3.34
Germanium (Ge)	ppm	2.63 ±3.86	5.24 ±8.05	3.63 ±4.56	13.6 ±12.7	20.4 ±18.1	4.19 ±4.45

(Continued)

TABLE 9. (Continued)

	Units	Pottsville Group	Allegheny Formation	Monongahela Formation	Illinois Basin	Western Interior	Rocky Mountain
Lanthanum (La)	ppm	10.2 $\pm$ 7.17	11.7 $\pm$ 9.04	7.94 $\pm$ 5.11	7.41 $\pm$ 7.55	19.4 $\pm$ 13.6	19.4 $\pm$ 13.6
Lead (Pb)	ppm	7.12 $\pm$ 6.33	11.6 $\pm$ 12.4	6.13 $\pm$ 5.70	21.0 $\pm$ 38.2	61.4 $\pm$ 63.8	5.57 $\pm$ 6.63
Lithium (Li)	ppm	18.6 $\pm$ 20.1	26.5 $\pm$ 33.2	18.2 $\pm$ 16.7	11.5 $\pm$ 23.2	8.79 $\pm$ 9.87	10.3 $\pm$ 9.86
Mercury (Hg)	ppm	0.14 $\pm$ 0.16	0.36 $\pm$ 0.71	0.19 $\pm$ 0.15	0.11 $\pm$ 0.09	0.17 $\pm$ 0.16	0.06 $\pm$ 0.09
Molybdenum (Mo)	ppm	2.39 $\pm$ 3.22	3.78 $\pm$ 3.70	2.38 $\pm$ 2.58	4.49 $\pm$ 5.89	5.51 $\pm$ 6.41	1.12 $\pm$ 0.67
Nickel (Ni)	ppm	13.3 $\pm$ 12.5	18.8 $\pm$ 18.1	10.9 $\pm$ 8.41	23.4 $\pm$ 34.9	29.0 $\pm$ 28.5	6.09 $\pm$ 9.21
Scandium (Sc)	ppm	3.38 $\pm$ 2.23	4.65 $\pm$ 3.18	3.23 $\pm$ 2.08	2.91 $\pm$ 1.67	3.15 $\pm$ 2.24	2.13 $\pm$ 1.70
Selenium (Se)	ppm	3.16 $\pm$ 2.03	4.23 $\pm$ 5.70	2.17 $\pm$ 1.37	2.72 $\pm$ 1.92	4.01 $\pm$ 5.75	1.56 $\pm$ 0.93
Silver (Ag)	ppm	0.05 $\pm$ 0.05	0.07 $\pm$ 0.07	0.04 $\pm$ 0.04	0.09 $\pm$ 0.12	0.36 $\pm$ 0.44	1.29 $\pm$ 1.58
Strontium (Sr)	ppm	98.0 $\pm$ 88.5	88.0 $\pm$ 90.0	85.0 $\pm$ 88.8	37.3 $\pm$ 47.4	50.0 $\pm$ 98.7	127 $\pm$ 115
Thorium (Th)	ppm	2.85 $\pm$ 2.25	3.21 $\pm$ 2.57	2.19 $\pm$ 1.38	2.18 $\pm$ 2.22	5.76 $\pm$ 9.67	3.06 $\pm$ 2.22
Uranium (U)	ppm	1.65 $\pm$ 1.69	1.73 $\pm$ 2.01	1.50 $\pm$ 2.09	1.98 $\pm$ 2.91	3.76 $\pm$ 6.20	1.52 $\pm$ 3.23
Vanadium (V)	ppm	19.8 $\pm$ 15.6	24.6 $\pm$ 20.3	18.5 $\pm$ 13.1	19.9 $\pm$ 15.9	24.9 $\pm$ 25.3	12.2 $\pm$ 10.2
Ytterbium (Yb)	ppm	0.87 $\pm$ 0.36	1.11 $\pm$ 0.70	0.69 $\pm$ 0.46	0.66 $\pm$ 0.46	1.05 $\pm$ 0.74	0.66 $\pm$ 0.56
Yttrium (Y)	ppm	7.80 $\pm$ 5.58	9.03 $\pm$ 6.36	5.93 $\pm$ 3.87	6.50 $\pm$ 4.41	10.4 $\pm$ 7.83	7.62 $\pm$ 8.18
Zinc (Zn)	ppm	13.6 $\pm$ 20.2	34.4 $\pm$ 55.4	16.3 $\pm$ 14.5	130 $\pm$ 561	731 $\pm$ 2172	11.0 $\pm$ 14.7
Zirconium (Zr)	ppm	20.4 $\pm$ 20.9	27.3 $\pm$ 30.5	27.5 $\pm$ 30.3	23.9 $\pm$ 21.8	13.4 $\pm$ 10.2	26.0 $\pm$ 18.6

awhole coal basis

2.3 DISTRIBUTION OF SULFUR AND TRACE ELEMENTS IN COAL

While knowledge of the amounts of sulfur and trace elements in a given coal is useful, additional scientific and technological information could be obtained if the mode in which these elements occur is understood. For example, the importance of a given trace element as a catalyst in a synthetic fuels process or the potential for separation of selected trace elements during physical coal cleaning may depend upon whether the element is organically bound, occurs as a cation bound to an aluminosilicate, or is present as a sulfide. Several methods are available to aid in determining the mode of trace element occurrence. These methods include gravity separation to determine the "organic affinity" of an element, photomicrograph studies using scanning electron microscopy (SEM) to observe maceral/mineral relationships and mineral textures, and chemical analysis of elemental ratios of various major and trace elements. The remainder of this section is divided into four subsections corresponding to each of these three analytical techniques plus a subsection discussing selected geochemical models which have been developed to explain the fixation of sulfur and trace elements in coal.

2.3.1 Organic Affinity Studies

Much of the work done on trace elements in coal has sought to quantify the various elemental associations with respect to the organic versus the inorganic (i.e., the major minerals) materials in coal. The most common method used in this research has been to physically separate particles of crushed coal by conventional gravity separation techniques. To a lesser extent, but in the same line of research, leaching of coal samples by selected acids has been used to chemically dissolve the inorganic matter in the coal matrix.

The use of gravity separation methods to determine the mode of trace element occurrence can be misleading. That is, gravity separations indicate only the physical association of trace elements with extraneous minerals or the organic coal matrix, and thus provide only indirect information on the chemical and mineralogical mode of occurrence. A frequent misconception is that

an element having a high organic affinity value is in some way chemically bound to the organic structure of the coal. While chemical bonding does occur with some trace elements, trace elements with high organic affinity values can also occur in association with fine-grained minerals encapsulated in the lighter organic matrix. In these instances, gravity separation of fine-grained minerals depends on both the actual mode of elemental occurrence and the size to which the sample is ground.

In addition, much of the literature on organic affinity has been based on insufficient data to statistically support conclusions regarding organic affinity. Using previously published data, Balkissoon and Knehlmer (30) found that in many instances reported organic/inorganic affinities lacked sufficient data to be statistically significant and could have resulted from depositional conditions rather than any inherent elemental affinity for the organic or inorganic matter in coal. Despite these limitations, however, gravity separations have been widely used in trace element studies and can provide valuable scientific and engineering information, particularly with regard to trace element reductions during coal cleaning operations (see Section 3.1).

2.3.1.1 Studies Prior to 1970

The initial efforts to examine the distribution of trace elements in coal by use of organic affinity methods were those of Horton and Aubrey (31) and of Zubovic and co-workers at the U.S. Geological Survey (32, 33). Horton and Aubrey, using three hand-picked and gravity-separated samples of vitrain from an English coal seam, concluded that beryllium, germanium, gallium, vanadium, titanium, and boron occurred almost totally within the organic structure of coal while manganese, phosphorous, and tin were in the inorganic fraction. Zubovic et al. (33) examined 13 coal samples from the Eastern Interior Region of the U.S. and obtained generally similar results except for tin and zinc. Table 10 compares the findings of both projects for the 15 elements examined

TABLE 10. AVERAGE ORGANIC AFFINITY FOR SELECTED TRACE METALS

	Horton & Aubrey (31)	Zubovic (33)	Gluskoter ^a (11)
Germanium	100	87	102 (6-202)
Beryllium	75-100	82	83 (64-103)
Gallium	75-100	79	52 (15-81)
Titanium	75-100	78	31 (8-54)
Boron	75-100	77	77 (32-106)
Vanadium	100	76	65 (47-99)
Nickel	0-75	59	70 (37-101)
Chromium	0-100	55	48 (8-80)
Cobalt	25-50	53	76 (33-121)
Yttrium	ND ^b	53	ND ^b
Selenium	ND ^b	ND ^b	50 (28-60)
Molybdenum	50-75	40	22 (8-49)
Copper	25-50	34	57 (24-79)
Lead	ND ^b	ND ^b	32 (7-67)
Tin	0	27	28 (18-40)
Mercury	ND ^b	ND ^b	26 (8-44)
Lanthanum	ND ^b	3	45 (8-75)
Zinc	50	0	22 (8-53)
Arsenic	ND ^b	ND ^b	11 (7-27)
Cadmium	ND ^b	ND ^b	9 (8-10)

^a Average (range); based on 8 samples except for Ti (7), Mo (3), Ti (3), Hg (6), La (5), Zn (7), Cd (4).

^b Not determined.

by Zubovic, plus selected elements from Gluskoter et al. (11) (discussed below). Note that for some elements (Ge, Be, B), the three studies closely agree. For other elements (Ti, Zn) significant differences exist. Note also the range of organic affinity values reported by Gluskoter for different coals.

2.3.1.2 Illinois State Geological Survey

During the 1970s the Illinois State Geological Survey (ISGS) conducted a series of interrelated studies on the mode of trace element occurrence (11, 19, 34). The three major components of these studies addressed the level and variability of trace elements in various coals, the statistical correlations between various trace elements and the cause of such relationships, and the organic affinity of individual trace elements. Studies of the variability in

trace elements included samples of 166 coals from the Illinois Basin (114 samples), the eastern U.S. (23 samples) and the western U.S. (29 samples). Constituents evaluated included the ten major mineral oxides, 45 trace elements, sulfur, carbon, hydrogen, oxygen, and nitrogen. Analysis of the level and variability of trace elements is in general agreement with the data presented in Section 2.2.

The principal area of research by the ISGS was the evaluation of organic affinity of trace elements (11, 19). Several different techniques were used in this work including gravity separation, chemical demineralization, and ion exchange. A total of 27 coals were analyzed—15 from Illinois, six from Appalachia, and six from the west.

To express an element's organic affinity, ISGS (11) developed an index to estimate the distribution of a specific trace element relative to the organic and inorganic fractions of an individual coal. To determine the index value, washability tests were conducted on 3/8" x 28 mesh samples at specific gravities of roughly 1.28, 1.32, 1.40, and 1.60. Trace element contents of each specific gravity fraction were then measured. Using these data plus the amount of inseparable mineral matter in the 1.28 float, an adjusted washability curve can be developed for the cumulative amount of each trace element in the coal as a function of the percentage coal recovery in each specific gravity fraction (Figure 5). The adjustment for mineral matter in the 1.28 float is made to account for inseparable fine-grained minerals dispersed in the organic matrix. The organic affinity index is the ratio of the area under the adjusted washability curve divided by the total area of the square formed by the origin at the lower-left corner and the adjusted trace element content of the total sample at the upper-right corner. For a trace element predominantly associated with the inorganic fraction of the coal, the organic affinity index will be near zero. For a trace element found predominantly in the organic fraction, the index value can be greater than 1.00. Organic affinity indices for selected trace elements are presented in Table 11.

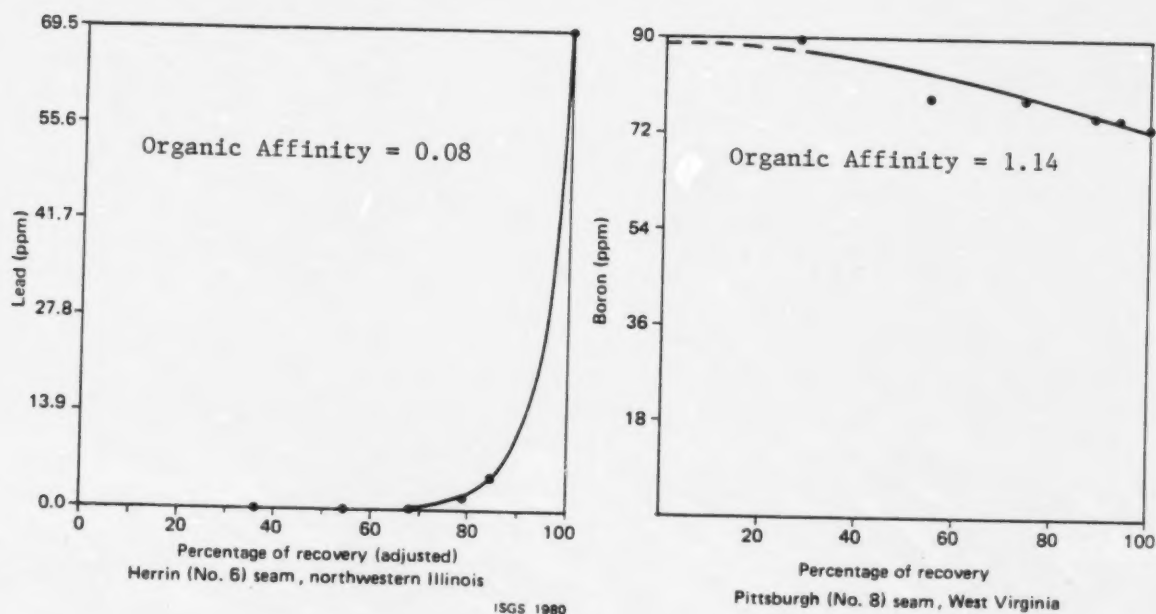


Figure 5. Adjusted Washability Curves for Lead and Boron for an Illinois No. 6 and a Pittsburgh Sample, Respectively

TABLE 11. ORGANIC AFFINITY VALUES FOR 27 ELEMENTS AND EIGHT COALS

	Bit (I) C18560	Bit (I) C17001	Bit (I) C16137	Bit (A) C18841	Bit (A) C19824	Bit (A) C18820	Bit (A) C18848	Sub (W) C19854	Sub (W) C19000	Mean & Sta. Deviation
As	.04						.05	.03	.11	.08±.06
B	.77	1.05	.05	.25	.11	.07	.37	1.24	1.09	.88±.28
Be	.87	1.03	.94	.81	1.14	.47	.77	.73	.79	.80±.13
Br	.92	ND*	.88	.53	.77	.87	1.20	.99	.83	1.00±.11
Cd	.07	.07	ND*	1.00	1.02	1.07	.45	.06	.99	.34±.33
Ce	.07	ND*	ND*	.66	.09	.63	.68	.89	.64	.55±.24
Co	.74	.65	.35	.53	.79	1.16	1.08	.80	.83	.77±.24
Cr	.77	.69	.37	.40	.58	.38	.60	.09	.54	.49±.19
Cu	.66	.56	.26	.47	.49	.55	.78	.44	.74	.55±.15
Ga	.15	.67	.41	.53	.79	.49	.64	.76	.38	.54±.18
Ge ¹	2.02	1.25	1.24	.62	ND*	.69	ND*	ND*	.06	.98±.62
Mo	ND*	ND*	.52	ND*	ND*	ND*	ND*	.83	ND*	.46±.32
Mn	.06	.35	.04	.43	.06	.40	.05	.04	.53	.21±.19
Ni	.75	.82	.36	.44	.62	.99	1.01	.64	.88	.72±.22
Pb	.32	.04	.05	.62	.04	.38	.68	.04	.06	.25±.18
Sb	.90	.68	.67	.41	.37	.55	.64	.95	.66	.65±.18
Se	.28	.69	.39	.36	.53	.46	.58	.05	.61	.44±.18
Sr	.07	ND*	ND*	1.03	.94	.89	.80	.98	.84	.79±.30
Th	.55	ND*	ND*	.23	.62	.29	.43	.56	.38	.44±.14
U	1.29	ND*	ND*	.79	.74	.40	.71	.58	.50	.72±.27
V	.97	.60	.58	.48	.57	.56	.75	.60	.74	.65±.14
Zn ¹	.04	.02	.04	.42	.31	.52	.21	.02	2.2	.41±.65
Org S	1.11	1.09	1.15	1.07	1.15	1.18	1.08	1.10	.95	1.10±.06
S	.45	.10	.54	.71	.81	.82	.74	.88	.88	.68±.27
Fe	.06	.04	.16	.30	.17	.67	.44	.02	.89	.31±.29
Mg	.27	.41	.32	.49	.04	.37	.07	.97	.95	.43±.31
Na	.64	.76	.43	.54	.71	.50	.20	.88	1.00	.63±.23
Ca	.06	.63	.04	.50	.04	.53	.34	.82	.82	.42±.30
Si	.45	.50	.09	.12	.39	.11	.17	.06	.10	.22±.16

¹Coal Rank, (Location: A = Appalachia, I = Illinois, W = West), sample number.

²1.16±.50 excluding sample C19824

³0.20±.19 excluding sample C19000

*Not Determined

Source: Reference 25 for all values except Ge; Ge from Reference 4.

As shown in Table 11, certain elements associated with plant growth (B, Be, Br, Ge, Sr, and organic S) are found almost exclusively in the organic fraction of the coal while several chalcophile elements (As, Pb, and Zn) are found almost totally in the mineral fraction. Ca, Mg, and Na exhibit high organic affinity in the lower rank western coals, but are more uniformly divided between the organic and inorganic fractions in bituminous coals. Despite these general trends, the variability in the data is significant. For example, Ge appears to occur almost exclusively in the inorganic fraction of sample 19824 while Zn occurs in the organic fraction of sample 19000. Other elements such as Cd and Fe show widely varying associations. The coals with high organic affinity values for Cd and Fe also have low sulfur contents, suggesting that Cd and Fe occur as fine-grained minerals intimately admixed with the organic fraction at low sulfur levels, but form coarser-grained sulfides in higher sulfur coals.

An alternative to gravity separation for determining organic affinity is to chemically demineralize a coal sample using various acids. In an effort to validate the above results based on gravity separation, ISGS demineralized coal samples in HNO_3 , HCl , and HF . Table 12 presents the average percent retention of trace elements in 12 chemically demineralized samples of Illinois No. 6 coal plus six coal samples from the eastern and western U.S. All samples were washed at a specific gravity of 1.4 to reduce pyrite content prior to chemical demineralization. While trends in these averages exist, variations within a region are frequently greater than the differences between regions.

The levels of trace and major elements remaining in the coal samples following chemical demineralization were compared with the gravity separation results and found to be generally similar for most elements. Where significant differences existed (Na, Ca, Mg, B, Ba, Be, Br, and Sr for some of the coals), ion exchange test using ammonium acetate accounted for a substantial portion of the discrepancy. The discrepancy between chemical versus physical demineralization methods is especially significant for the western low-rank coals where up to 70 percent of the Ca and Mg, almost all of the Na, and 40 percent of the Sr was ion exchangeable. Based on work at Grand Forks Energy

TABLE 12. MEAN CONCENTRATIONS AND MEAN RETENTION PERCENTAGES IN MINERAL-MATTER-FREE COALS*

Element	IL Herrin (No. 6)			Eastern			Western		
	Raw Coal	MMF	Retention Percentage	Raw Coal	MMF	Retention Percentage	Raw Coal	MMF	Retention Percentage
Si	2.60±.6%	56±19	0.2	2.41±.4%	60±12	0.2	1.39±.7%	56±20	0.4
Al	1.28±.3%	61±14	0.5	1.94±.6%	144±100	0.7	1.06±.4%	76±58	0.7
Fe	1.96±.9%	96±53	0.5	1.0±.5%	107±75	1	0.4±0.1%	71±77	2
Ca	0.96±.8%	38±22	0.4	0.62±.5%	71±72	1	1.66±1.2%	61±69	0.4
Na	592±472	5.8±4	1	481±248	10±11	2	960±1410	7.8±6	0.8
Mg	0.06±.03%	26±10	4	0.06±.05%	25±22	4	0.20±0.1%	17±5	0.9
K	0.16±.05%	9.3±14	0.6	0.19±.09%	1.8±1	0.1	0.03±.03%	—	—
Ti	0.07±0.02%	30±14	4	0.10±.04%	76±68	8	0.05±.02%	31±16	6
P	52±30	4.1±3	8	85±57	2.3±2	3	96±47	—	—
Mn	88±75	0.72±1	0.8	20±10	2.4±3	12	55±38	1.8±2	3
S	3.9±1.4%	1.7±.5%	44	2.0±1.7%	1.0±.7%	50	0.73±.2%	0.42±.1%	58
Organic S	1.7±.5%	1.7±.5%	98	1.0±.74%	1±.7%	100	0.45±.1%	0.42±.1%	93
Be	1.5±.8	0.04±.03	3	0.70±.2	0.05±.03	7	0.40±.1	0.03±.03	8
B	148±81	8.1±2	5	53±42	14±7	26	59±33	7.3±6	12
Sc	29±.8	0.4±.3	1	4.9±2	1.2±0.9	24	1.4±.4	0.29±.2	21
V	37±17	6.5±4	18	48±22	9.3±13	19	17±12	2.3±2	14
Cr	28±13	5.7±3	20	20±7	7.3±4	36	2.7±3	1.1±.3	41
Co	5.3±3	0.4±.2	8	6.8±6	3.5±4	51	1.3±0.8	0.5±0.5	38
Ni	21±8	6.0±5	28	12±3	2.8±2	23	4.2±2	—	—
Cu	20±9	5.0±3	25	22±8	3.8±2	17	14±8	3.6±3	26
Zn	832±1700	<5	—	29±45	<1	—	10±9	—	—
Ga	3.2±1	0.60±.1	19	4.7±2	1.2±0.6	26	2.7±2	0.73±.8	27
As	6.8±8	<1	—	10±8	<1	—	1.8±2	0.5±.3	28
Se	2.6±.9	0.34±.2	13	3.1±2	0.58±.2	19	1.4±.4	0.39±.2	28
Br	8.9±7	6.0±4	67	11±9	6.7±6	61	1.1±.4	1.8±2	163
Rb	16.8±7	<1	—	14±4	—	—	1.8±.9	—	—
Sr	31±11	4.1±3	13	121±53	29±19	24	185±66	—	—
Mo	6.8±4	0.90±0.6	13	6±5	—	—	3.7±3	—	—
Cd	—	—	—	—	—	—	—	—	—
Sb	1.1±1	0.4±.3	30	2.3±2	0.40±.3	17	1.1±1	0.38±.2	34
Cs	1.3±.7	0.04±.03	3	1.4±.6	0.08±.08	6	0.19±.2	—	—
Ba	237±445	3.3±1.5	1	146±61	20±9	13	498±175	13±14	3
La	6.8±2	0.7±.2	10	13±6	2.8±1.2	22	5.7±2	1.3±.7	23
Ce	14.7±8	1.1±.4	7	21±8	3.2±.7	15	9.7±3	1.7±1	18
Sm	1.1±.4	0.30±.01	27	2.2±.8	0.54±.3	24	0.69±0.2	0.21±.1	30
Eu	0.30±.1	0.06±.03	20	0.4±.2	0.12±.05	30	0.17±.07	0.05±.02	29
Tb	0.26±.1	—	—	0.02±.09	—	—	0.15±.04	—	—
Dy	1.0±.4	0.26±.1	26	1.7±0.7	—	—	0.60±0.2	—	—
Yb	0.58±.2	0.13±.06	22	0.58±.2	0.19±.04	33	0.39±.2	0.11±.04	28
Lu	0.09±.02	0.03±.01	33	0.13±.08	0.06±.03	46	0.07±.02	0.02±.01	28
Hf	0.70±.3	0.09±.04	13	1.3±.4	0.29±.2	22	0.99±.2	0.26±.1	26
Ta	0.17±.07	—	—	0.37±.3	0.09±.01	24	0.13±.05	—	—
W	0.68±.4	—	—	0.57±.4	0.26±.3	46	0.80±.3	—	—
Pb	29±27	—	—	8.9±9	—	—	4.1±1	—	—
Th	2.1±0.8	0.52±.2	25	4.1±2	1.0±.4	23	2.0±.9	0.80±.2	40
U	2.3±2	0.22±.1	10	1.2±1	0.27±.2	22	0.98±0.2	0.13±.1	13
ISA†	197	—	—	—	—	—	—	—	—

*All values in ppm unless noted. Less than values were not included in calculation of means.
†Internal surface area by CO₂ method (values in m²/g).

Source: Reference 19

Technology Center (35) and by Miller and Given (10), it is believed that these exchangeable ions are bound to carboxyl and other hydrophylic groups in the low-rank coals. These groups are lost during the advancement in coal rank from lignite to bituminous (see Section 2.1.1.2). Groenweld (36) notes that the high levels of Na, Ca, and Mg in Northern Great Plains lignites appear to be associated with the movement of groundwater through the seams.

2.3.1.3 U.S. Department of Energy-Pittsburgh Energy Technology Center

Several studies on the removal of sulfur and trace elements by gravity separation methods have been conducted by the Pittsburgh Energy Technology Center of DOE (previously part of the Bureau of Mines). Cavallaro, Johnston, and Deurbrouck (37) tested 455 coal channel samples to determine the potential for ash and sulfur reduction from coal cleaning. A more recent study by Wizard, Cavallaro, and Deurbrouck (38) on the ash and sulfur reduction potential of Pennsylvania bituminous coals has been published. Similar additional studies for Ohio, West Virginia, and the western U.S. have been initiated, but results have not yet been published.

Cavallaro, Gibbon, and Deurbrouck (39) conducted gravity separation tests on ten coals to determine the potential for removal of eight trace elements. Results of these studies are presented in Section 3.1.4.2. While significant variations in trace element reduction potential exists between the coals tested, general agreement exists between these values and the organic affinity index developed for these elements by ISGS.

2.3.1.4 Bituminous Coal Research, Inc.

Bituminous Coal Research, Inc. (BCR) (40, 41) has conducted tests on 26 coal samples to determine the efficiency of sulfur and trace element removal by gravity separation. These tests have been funded by DOE and are generally similar in approach and reporting format to Cavallaro et al. (39). Results of the study are presented in Section 3.1.4.2. In addition to percentage reduction estimates, BCR also examined the data for correlations between trace

element content and other coal properties, including petrographic constituents. Additional studies to examine trace element reduction as a function of coal mineralogy have been proposed to DOE, but have not yet been funded (42).

2.3.2 Photomicrographic Studies

As indicated in Section 2.3.1, gravity separation methods provide only circumstantial evidence as to the mode of trace element occurrence in coal. To directly investigate modes of occurrence and organic/inorganic associations, photomicrographic methods, using optical and scanning electron microscopes and microprobes, are extremely valuable. While providing the advantage of allowing analysis of individual macerals and minerals, microscope/microprobe techniques usually examine only a small portion of the entire sample, and are thus generally not appropriate for bulk characterization of coal samples.

The following two sections review work conducted at USGS and at Los Alamos Scientific Laboratory which have used microscope/microprobe techniques to examine trace elements in coal and coal preparation plant refuse, respectively. Results of these two studies in terms of modes of trace element occurrence are summarized in Table 13.

2.3.2.1 U.S. Geological Survey/University of Maryland

During the late 1970s, R. B. Finkelman of the USGS began a series of studies examining the mode of trace element occurrence in coal using a scanning electron microscope equipped with an energy dispersive X-ray detector to determine the elemental makeup of micron-sized particles. These studies included in-depth analysis of the Waynesburg and Upper Freeport bituminous coals from the Appalachian Basin plus a survey of 80 samples from throughout the U.S. and 20 samples collected outside the U.S. Based on these studies, Finkelman postulated the primary modes of occurrence for 47 trace elements plus the family of rare earth elements (atomic numbers 57-71) as shown in

TABLE 13. TRACE ELEMENT MODES OF OCCURRENCE IN COAL

Element	USGS/University of Maryland	Los Alamos Scientific Laboratory
Antimony (Sb)	probably as an accessory sulfide in the organic matrix	sulfide (with pyrite)
Arsenic (As)	solid solution in pyrite	sulfide (with pyrite)
Barium (Ba)	barite, crandallites, and other Ba-bearing minerals	sulfate, phosphate
Beryllium (Be)	organic association, clay	clay
Bismuth (Bi)	accessory sulfide, perhaps bismuthinite	clay
Boron (B)	generally organic association, illite	organic association
Bromine (Br)	organic association	clay
Cadmium (Cd)	sphalerite	organic association
Cesium (Cs)	inorganic association, clays, feldspars, or micas	clay (sulfide with Zn)
Chlorine (Cl)	organic association, NaCl	clay
Chromium (Cr)	clays	organic association
Cobalt (Co)	associated with sulfides, such as pyrite and linnaeite	clay (with Al)
Copper (Cu)	chalcocopyrite	clay (possibly as sulfide)
Fluorine (F)	unclear, probably several inorganic associations, such as apatite, amphibole, clays, and mica	sulfide (mainly in clay)
Gallium (Ga)	clays, organic association, sulfides	clay, phosphate
Germanium (Ge)	organic association, rarely in silicates, sphalerite	mineral phase
Gold (Au)	native gold, gold tellurides	oxide (in clay)
Hafnium (Hf)	zircon	oxide (in clay)
Indium (In)	sulfides or carbonates	oxide (in clay)
Iodine (I)	organic association	oxide (in clay)
Lead (Pb)	pyrite, galena, PbSe, coprecipitated with Ba	sulfide
Lithium (Li)	clays - illite, mixed-layer	clay
Manganese (Mn)	siderite, calcite	sulfides, carbonate, clay
Mercury (Hg)	solid solution with pyrite	sulfide (with pyrite)
Molybdenum (Mo)	unclear, probably with sulfides, or organic constituents	sulfide (with pyrite)
Nickel (Ni)	unclear, may be with sulfides, organic constituents, or clays	sulfide (mainly in clay)
Niobium (Nb)	oxides	phosphates (in clay)
Phosphorus (P)	various phosphates, some may be organically associated	phosphates
Platinum (Pt)	perhaps native Pt alloys	phosphates
Rare Earth Elements (REE)	phosphates	phosphates
Rhenium (Re)	sulfides or organic constituents	phosphates
Rubidium (Rb)	probably illite	phosphates
Scandium (Sc)	unclear, clays, phosphates or may have organic association	clay
Selenium (Se)	organic association, as PbSe in Appalachian coals, pyrite	clay
Silver (Ag)	probably silver sulfides, but may be complex	sulfide (with pyrite)
Strontium (Sr)	carbonates, phosphates, organic association in low rank coals	oxide
Tantalum (Ta)	oxides	oxide
Tellurium (Te)	unclear	clay
Thallium (Tl)	sulfides, probably epigenetic pyrite	clay
Thorium (Th)	REE phosphates	clay (possibly as phosphate)
Tin (Sn)	inorganic, tin oxides or sulfides	oxides (in clay)
Titanium (Ti)	titanium oxides, organic association, clays	clay (possibly as phosphate)
Tungsten (W)	unclear, may have organic association	clay (possibly with iron oxide)
Uranium (U)	organic association, zircon	clay
Vanadium (V)	clays (illite)	sulfide (mainly in clay)
Yttrium (Y)	REE phosphates	oxide, silicate
Zinc (Zn)	sphalerite	oxide, silicate
Zirconium (Zr)	zircon	oxide, silicate

Table 13. A detailed discussion of each element, including findings by earlier investigators, is presented in Finkelman's Ph.D. thesis to the University of Maryland (12).

The findings of these studies are of specific importance to understanding the environmental fate of trace elements in coal, particularly as relate to trace element partitioning during coal cleaning. For example, Finkelman found a number of trace elements concentrated in micron-sized minerals disseminated throughout the organic matrix: Zn and Cd in sphalerite; Cu in chalcopyrite; Zr and Hf in zircon; and rare earth elements Y and Th in phosphates. Because of their small grain size and close association with the organic matrix, these elements may have a high apparent organic affinity based on float-sink tests. On the other hand, As and Hg were found to be in solid solution in coarser-grained pyrites: they are therefore more likely to be removed with the sink material. In most coals, Pb was found as a sulfide and as a substitute for Ba in various barium-bearing minerals. In the Appalachian Basin, lead selenide was found more frequently than lead sulfide.

Finkelman also found significant amounts of Se, Br, Be, B, Ge, Ti, and U to be directly associated with the organic matter. However, mineral forms of certain of these elements are also present. For example, Ti occurs as rutile (Ti-oxide) and in clays while uranium can occur as uranite (U-oxide) and in detrital minerals such as zircon.

Another result of this work was to discount the significance of statistical correlations between individual elements as an indication of a common mode of occurrence. While common modes of occurrence were identified for some elements (e.g., Cd and Zn in sphalerite), in many instances no such associations were found. Finkelman concluded that in these latter instances it is a common source of origin for the elements (e.g., detrital influx) that causes the correlations.

Additional discussion of Finkelman's work on the origin of mineral matter in coal is presented in Section 2.3.4.

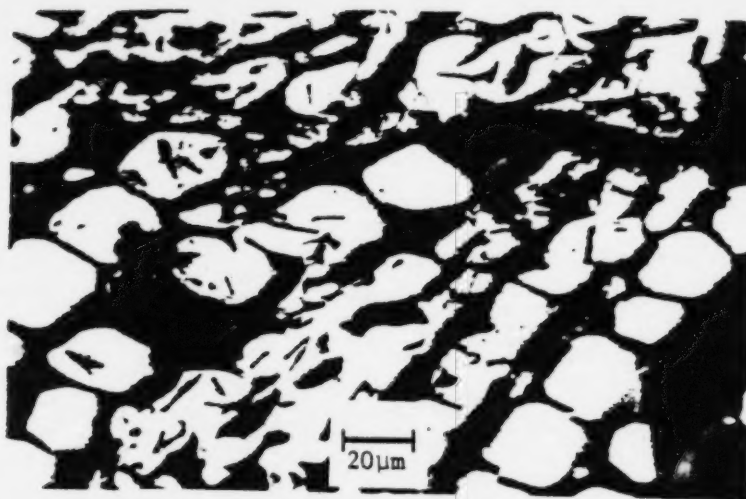
2.3.2.2 Los Alamos Scientific Laboratory

The micromineralogy of coal preparation wastes has been analyzed at Los Alamos Scientific Laboratory (LASL) through the use of high resolution optical techniques (43). In this work, photomicrographs and elemental determinations were made of coal cleaning refuse using microscopic and microprobe methods. Because the chemical and mineralogical properties of coal refuse are largely unaltered from those found in the mineral fraction of raw coal, these studies are directly transferable to the discussion of trace element associations in coal.

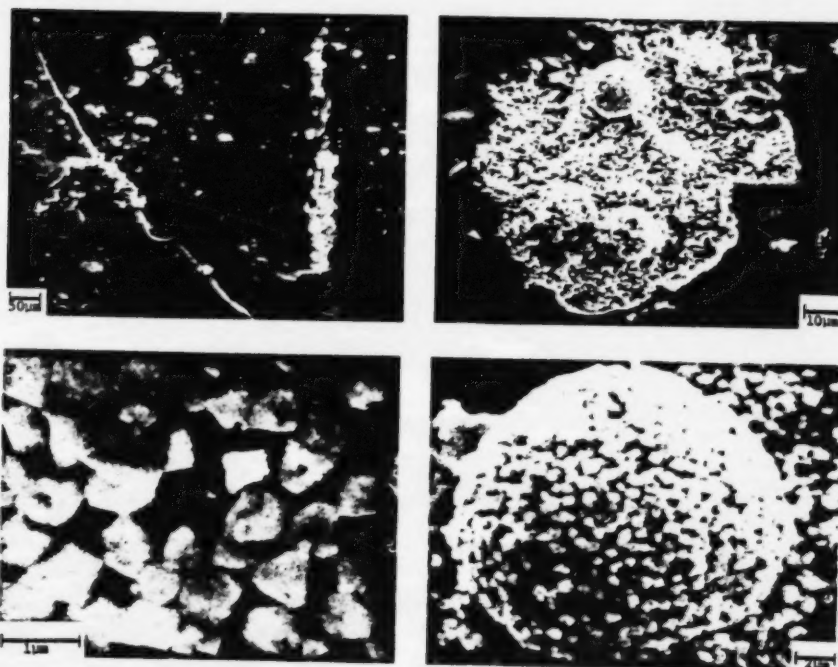
Using these techniques, Williams and other researchers at LASL have been able to directly observe the microstructure of coal. Williams found significant amounts of mineral matter in coal as very finely divided mineral grains which simply "tag along" with the organic matter rather than being chemically bound. Even after substantial size reduction of the coal (less than 20 mesh) and extensive gravity separations, significant amounts of pyrite and marcasite were still present in the cleaned fraction. Figure 6 illustrates the occurrence of pyrite (light-colored material) within the cell structure of a coalified plant (dark material) and the formation of pyrite in a coal micropore roughly 50 microns wide. Williams concludes that the percentage of organically bound elements constitutes a limited portion of the total trace elements present.

2.3.3 Elemental Ratios of Major and Trace Elements

The third line of study regarding the origin of trace elements in coal is the study of the elemental ratios of major and trace elements. The major area of study has been the comparison of the levels of rare earth elements (REE) in coal samples. Figure 7 is a plot of the concentrations of the REEs normalized to the level of REEs in chondrite for two bituminous coals, a lignite of varying ash contents (shown in parentheses on a percentage basis), and the average of 40 North American shales. The two bituminous coals are plotted based on the ash alone while the lignite is plotted on a whole-coal basis. As can be seen, the bituminous coal ashes and the shale values are very similar,



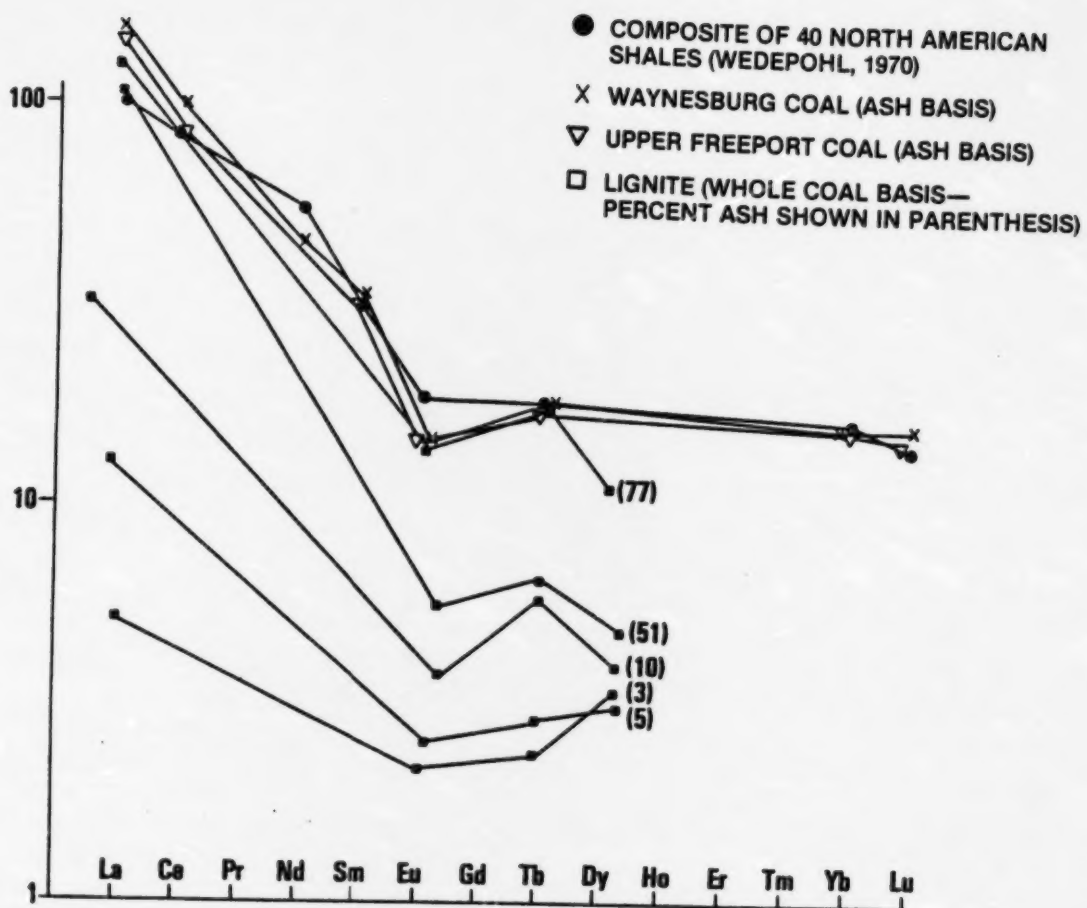
Pyrite replacement in the cells of a coalified plant.



Framboidal pyrite in a coal pore.

Source: Reference 32

Figure 6. Photomicrographs of Pyrite in Coal



Source: Reference 17

Figure 7. Chondrite-Normalized Rare-Earth Element Distribution Patterns for Several Coal Samples

suggesting that the REE distribution in coal is determined mainly by detrital influx. This is further supported by the lignite data which show that lignites low in ash content (i.e., those believed to include little detrital material) have REE distributions distinctly different from those in shale. However, as ash levels increase, presumably due to increasing concentrations of detrital material, the distribution of REE closely approaches that of the bituminous ashes and the averaged shale values.

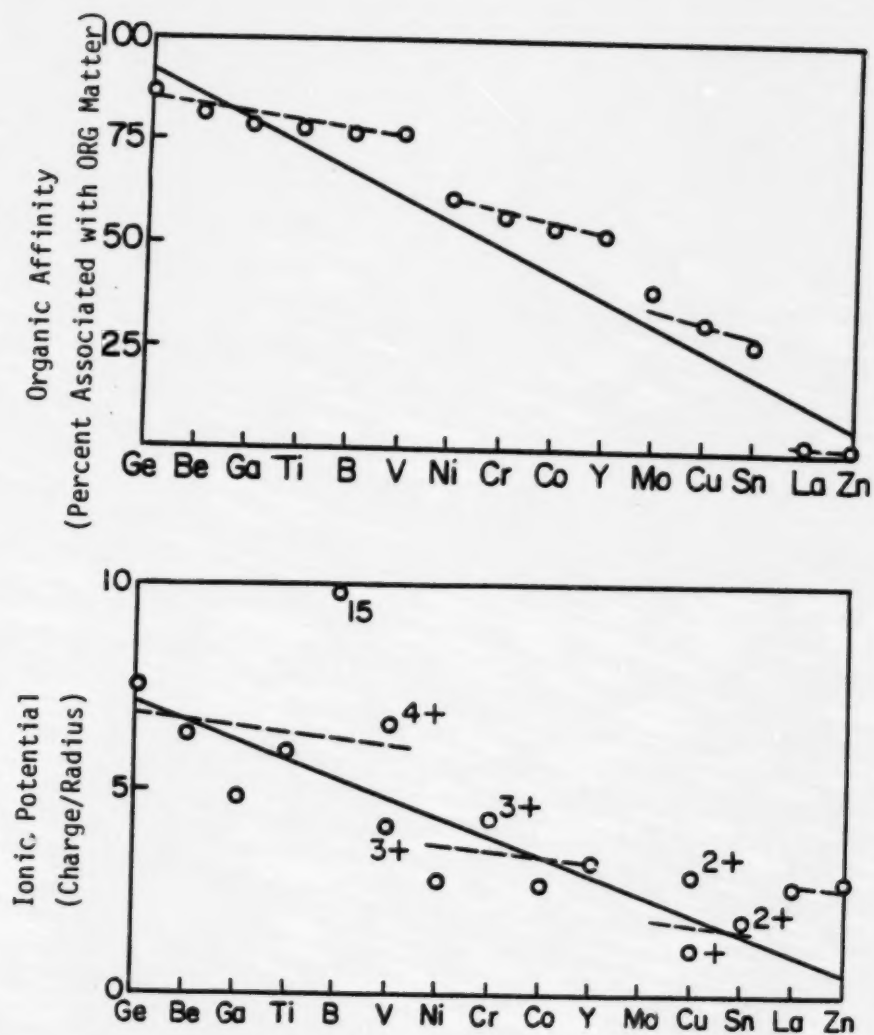
2.3.4 Conceptual Models for Trace Element Modes of Occurrence

Conceptual models depicting the mode of trace element occurrence in coal have been developed by several investigators. Three of the models widely discussed in the literature are presented below. Interestingly, each of these models was developed by personnel who were employed by the USGS at the time of their publication. The later two models were developed at roughly the same time and reflect fundamental differences in the interpretation of basic geological and geochemical data on the origin of mineral matter in coal.

2.3.4.1 Chelation and Depositional Environmental Models

Zubovic developed the first models for explaining the organic and inorganic association of trace elements in coal. Zubovic's efforts focused on the prediction of organometallic complexes based on an element's ionic potential and chelate stability (44) and on the depositional environment of the coal (45). Empirical data used to test the model were primarily taken from earlier work on the Eastern Interior Region (32, 33) and organic chemistry studies by others.

Zubovic (44) suggests that within the peat-forming environment, organic ligands and sulfide anions compete for the available chalcophile cations. Whether a specific cation becomes attached to the organic ligand or to the sulfide anion will depend on the relative concentration of these bonding sites and the strength of resulting bonds. As shown in Figure 8, for most elements a strong correlation exists between an element's organic affinity (see Section



Source: Reference 41

Figure 8. Relation of Organic Affinity and Ionic Potential of the Elements in Order of Decreasing Organic Affinity.

2.3.1.1) and its ionic potential (the ion's charge divided by its radius). This relationship also correlates with the strength of chelate bonds formed by the bivalent ions of most of these elements. For copper and zinc, which do not display this correlation, Zubovic suggests that 1) copper in the physico-chemical environment of a peat swamp would exist as a univalent ion and therefore would not have as high an ionic potential as a bivalent ion and 2) for copper and zinc, the bonding strength for their sulfides is greater than for their chelates. Thus the formation of organic chelates of zinc and copper would occur only if there was insufficient hydrogen sulfide available in a specific swamp area. Further, chelates of elements having a low chelate bonding strength could be displaced from the organic fraction at a latter time by the influx of elements capable of forming stronger bonds. The replacement of weak chelates by metals forming stronger chelates can result in the highly enriched levels of germanium, vanadium, and uranium found at the tops and bottoms of coal seams and in isolated, lenticular coal beds.

Zubovic also suggests that, based on their chelate strength (46), certain elements (trivalent vanadium, nickel, copper, and most of the other transition metals) are more likely to complex at nitrogen donor sites found in chlorophyll and amino acids. Other elements (gallium, germanium, titanium, tin, tetra- and pentavalent vanadium, and cobalt) will prefer chelation with the oxygen donor sites in lignins. Beryllium, chromium, and iron have equal affinity for both complexing agents. The retention of amino acids and lignins in coal may be partially attributable to the highly stable chelate complexes. Zubovic believes that chelate formation was limited to the early stages of coalification and, except for substitution reactions by more stable elements, later retention of metals by the organic fraction of coal is as simple complexes and not as chelates.

Zubovic (45) later postulated the relationship between trace elements and depositional environments. Four key parameters are identified:

1. Rate of subsidence for the depositional basin,
2. Rate of uplift for the upland drainage area,

3. Types of rocks being eroded in the source area and being deposited in the peat-forming basin, and
4. Ratio of the drainage area size to the volume of organic accumulation.

The first parameter influences the rate of organic accumulation in the swamp while the second and third parameters influence the ratio of detrital minerals to precipitates. The fourth parameter influences the concentration of minerals; where the ratio is large the coals will contain high levels of minerals and trace elements, and vice versa. Zubovic notes the concentration of trace elements occurring as strong chelates is higher near the boundary of the coal basin than in the center, suggesting the capture of these elements as they entered the ancient swamp. Elements forming weak chelates and sulfides, however, tend to be evenly distributed throughout the basin. Zubovic notes an exception to the uniformity of chalcophile elements in areas of known mineralization. The low trace element levels in coals of the Powder River Basin of Wyoming and Montana may be attributable to the large size of these coal deposits and thus the substantial dilution of trace elements introduced from surrounding areas.

2.3.4.2 Detrital and Authigenic Minerals Model

As discussed in Section 2.1.2.2, Cecil et al. (15) recognize five potential sources for the minerals in coal. On a quantitative basis, authigenic minerals formed from elements contained in the original plant matter and detrital minerals carried into the swamp by water and wind account for the majority of the inorganic matter in most coals. Determining the relative contribution of these two sources has been of interest to coal scientists for many years. As analytical tools improved during the 1970s, distinction between these two sources of mineral occurrence became a major area of research and debate.

Traditional thought has been that most coals contain both authigenic and detrital minerals. Using textural evidence obtained from microscopic studies, Finkelman (12) concluded that significant morphological differences exist between authigenic and detrital minerals. Using these differences to conduct a detailed evaluation of minerals in the Upper Freeport and Waynesburg coal seams, Finkelman concluded that roughly half of the minerals in these two coals were derived from detrital sources. However, for certain low-ash coals (such as the Indiana Block examined by Zubovic (21)), detrital minerals may be absent or negligible.

Using textural evidence plus chemical (see Section 2.3.3) and mineralogical information, Finkelman (16) subdivides the various minerals in coal into two distinct suites. The minerals contained in each of these two suites and the corresponding maceral and textural relationships are shown in Table 14. As noted in Section 2.1.2.2, Finkelman estimated that detrital minerals are generally negligible only in coals containing less than five percent ash.

2.3.4.3 Authigenic Minerals Model

Cecil, Stanton, Dulong, and others at the U.S.G.S. (9, 15) have focused on explaining the origin of mineral matter in coal as a function of the authigenic materials found in the ancient swamp. To date, most of the supporting studies have been conducted on the Upper Freeport Formation near Homer City, Pennsylvania. The primary objectives of the first phase of this work were to determine the geologic factors controlling variability in 1) total and pyritic sulfur, 2) forms and size of pyrite, 3) concentration of minerals including trace element distributions, 4) dominant mineral phases, and 5) mineral-matter/maceral associations.

Based on detailed geologic and geochemical analysis, Cecil et al. (15) have developed a conceptual model of sedimentation and peat accumulation in the Upper Freeport and correlated specific characteristics of the coal to ancient environmental conditions. Major determinants in Cecil's model are the availability of calcium carbonate source rocks, the source of water supply (fresh versus marine) and ratio of rainfall to evaporation, and the relation-

TABLE 14. CHARACTERISTICS OF SYNGENETIC COAL MINERALS

	Authigenic	Detrital
Mineral Relationships	Kaolinite Sulfides Carbonates Crandallite Group Apatite Barite	Illite Mixed-Layer Clays Quartz Zircon Rutile Feldspar
Maceral Relationships	Inertinites Vitrinite	Carbominerite Fragmented Macerals
Textural Relationships	Dispersed Pores, Pods, or Isolated Grains Exhibits Crystal Faces Intimately Intergrown	Banded Aligned Subangular to Subrounded Intergrowths rare (some rutilated quartz)

Source: Reference 16

ship of ancient plants to their environment. Based on theoretical and empirical evidence on peat compaction and coalification, Cecil et al. conclude that the major source of ash in the Upper Freeport and in most commercially valuable coals is the inherent ash forming material in the original plant matter and that detrital contributions are much smaller than believed by most other investigators.* Cecil et al. (9) note that due to normal organic matter losses during the coalification processes, a peat containing the equivalent of 10 percent ash will result in a coal with 18 percent ash. Ash enrichment in more severely degraded peats can be even higher.

*The Upper Freeport coal examined by Cecil et al. is the same coal examined by Finkelman (Section 2.3.4.2). Cecil et al. conclude the mineral matter in the coal is almost entirely authigenic while Finkelman estimated that it is roughly 50 percent detrital.

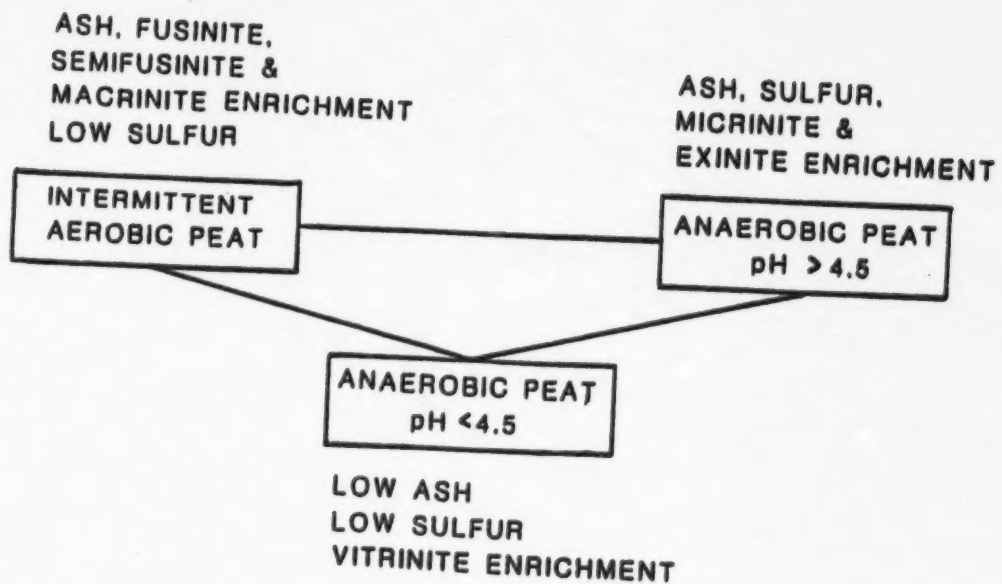
The groupings of macerals, minerals, and major and minor elements developed from statistical analysis of Upper Freeport coal samples are shown in Table 15. Group I components are mainly associated with ash in the coal. Cecil suggests the statistical correlation of these elements is due to a common source of materials, namely authigenic plant matter; detrital sources are of negligible importance. Group II components are associated with the sulfur in the coal and are controlled by the swamp pH, ionic strength of interstitial water, and microbial activity.

A generalized model of the maceral and mineral content of a coal can be defined as a function of the acidity of the ancient bog as shown in Figure 9. In the absence of calcium carbonate or other neutralizing agents (e.g., influx of marine waters), low pH conditions ($\text{pH} < 4.5$) will retard bacterial activity and promote the leaching of mineral matter and trace elements from the bog. During periods of high rainfall, leached materials will be washed from the swamp; resulting coals will have low ash and trace element levels. Higher bacterial activity associated with higher pH values will decompose humic matter and increase the relative amount of ash as well as liptinite and inertinite macerals in the resulting coal.

TABLE 15. GROUPING OF MACERALS, MINERALS, AND ELEMENTS IN UPPER
FREEPORT COALS BASED ON NONPARAMETRIC ASSOCIATIONS

Group I		Group II
Macerals	Vitrinite Fusinite Semifusinite	Sporinite Micrinite
Minerals	Quartz Illite Kaolinite	Pyrite Calcite
Elements, Oxides, and Sulfur forms	SiO ₂ Al ₂ O ₃ MgO Na ₂ O K ₂ O TiO ₂ B Ba Be Cd Ce Cr Cs	Cu Eu F Ga Gd Hf La Li Lu Nb Nd Ni Pb
	Rb Sb Sc Se Sm Sn Tb U V Y Yb Zn Zr	CaO Pyritic Sulfur Total Sulfur Organic Sulfur Fe ₂ O ₃ As Ge Hg

Source: Reference 15.



Source: Reference 9

Figure 9. Hypothetical Model Illustrating Possible Controls on Mineral Matter and Maceral Variation in Coal

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SECTION 3

EXISTING KNOWLEDGE ON THE RELATIONSHIPS BETWEEN COAL PROPERTIES AND UTILIZATION TECHNOLOGIES

Section 3 reviews the existing information base regarding the importance of coal properties relative to environmental control systems for sulfur and trace elements. With the exception of coal cleaning, coke production, and direct liquefaction, the importance of sulfur and trace element distribution has received little attention. This is not to say that the quantities of sulfur and trace elements have not been of concern, but rather that the mode of occurrence and distribution of these elements (e.g., the specific mineral form(s) in which a particular trace element occurs) has been given only limited consideration in the development, design, and application of most coal utilization technologies.

This section is divided along technology lines, each focusing on existing knowledge of how the mode of occurrence and distribution of sulfur and trace elements impacts that technology. Section 3.1 reviews coal cleaning, 3.2 combustion, 3.3 synthetic fuels (primarily gasification), and 3.4 waste disposal.

3.1 PREPARATION

3.1.1 Introduction

In its fullest sense, coal preparation involves the initial grinding and sizing of raw coal, cleaning of the coal to remove mineral matter and sulfur, and the dewatering, drying, and final sizing of coal prior to its use. Of primary focus in this section is the cleaning step and, to a lesser extent, the initial handling and sizing of raw coal prior to its cleaning.

Several distinct processes can be used to clean raw coal. The most commonly used approach is the mechanical separation of inorganic minerals based on the difference in specific gravity of various minerals (s.g.=2.0-4.0) and

pyrite (s.g.=5.0) versus the organic coal fraction (s.g.=1.15-1.5). This approach involves the use of gravitational and centrifugal forces in conjunction with water or a dense fluid media and currently accounts for roughly 95 percent of all coal cleaning in the U.S. The tendency of coal particles to selectively adhere to air bubbles is used for the cleaning of finely ground coal (<28 mesh = 0.60 mm) and accounts for most of the remaining five percent of coal cleaning tonnage. Additional approaches which have been proposed, but not commercially demonstrated, include using the magnetic properties of iron pyrite and the chemical reaction at elevated temperature and pressure of coal with various chemical reagents. The removal of trace elements and sulfur from raw coal discussed in this report is based entirely on the use of mechanical cleaning techniques, commonly referred to as physical coal cleaning or coal washing.

During coal washing, trace elements and sulfur are divided into a "float" fraction primarily containing the lighter organic materials and fine-grained "inherent ash" in coal and a "sink" fraction consisting mainly of clays, shales, pyrites, and other "extraneous" minerals.⁹ While the purpose of coal cleaning is the removal of ash-forming materials and sulfur from raw coal, the distribution of trace elements in the coal is also affected. Although a thorough understanding of the response of various coals to sulfur and trace element removal during coal preparation does not yet exist, significant insight has been developed through work by the Pittsburgh Energy Technology Center (1,2) and Los Alamos Scientific Laboratory (3,4) of DOE, the Illinois State Geological Survey (ISGS) (5,6), Bituminous Coal Research, Inc. (7,8), EPA (9-11), and USGS (12). A more complete bibliography of 1,076 publications was published in 1981 (13).

⁹The terms "inherent" and "extraneous" are defined in Section 2.1.

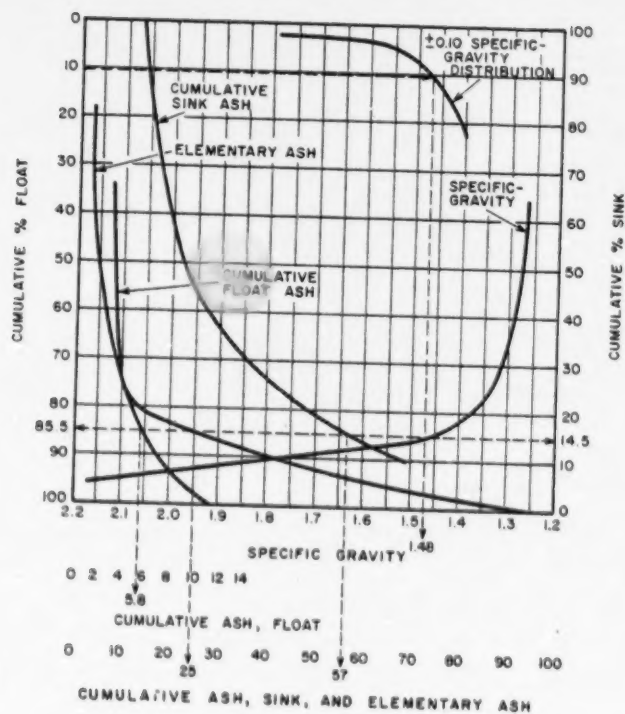
3.1.2 Coal Washing

PCC processes are based almost entirely on the use of the specific gravity of individual particles to separate coal into float and sink fractions. Chemical reactions and the conversion of mineral forms due to high temperature (as occur in combustion and synthetic fuels processes) are negligible in PCC. As such, the most important parameters in coal cleaning and the redistribution of trace elements and sulfur are associated with the physical properties of the coal and the mechanical aspects of the cleaning process.

Existing knowledge of coal cleaning is based almost entirely on empirical data of how a particular coal or piece of equipment has operated during previous applications or during a specified test procedure. While substantial empirical data are available, detailed understanding of how various coal properties influence the washability of coal does not yet exist. As a result, washability tests are generally conducted to obtain information on the response and variability of a specific coal.

The potential for removal of mineral matter and sulfur from a specific coal is evaluated through the use of washability studies conducted at a series of preselected specific gravity levels. The objective of the tests is to determine the distribution of coal versus mineral matter and sulfur between the float and sink fractions over the range of specific gravities. The size to which the coal is ground, the separating fluid used, and other testing methods frequently vary between laboratories and for different coals and anticipated coal usages.

Figure 10 is an example set of washability curves and related float-sink data describing the distribution of ash for a specific coal. Similar curves can be drawn for sulfur or other coal constituents. From these curves it is possible to estimate the percentage of ash (or other contaminant) in the cumulative float or sink fraction, the rate of change in ash content, and the quantity of "near-gravity" material at a selected specific gravity value. Near-gravity material represents feed coal particles which have a specific



Float-and-Sink Data

(1) Specific gravity	Individual Fractions			Cumulative Float			Cumulative Sink		
	(2) Wt %	(3) Ash %	(4) Ash prod.	(5) Wt %	(6) Ash prod.	(7) Ash %	(8) Wt %	(9) Ash prod.	(10) Ash %
Float 1.27	34.5	2.8	96.6	34.5	96.6	2.8	100.0	1293.1	12.9
1.27 × 1.30	28.4	3.9	110.8	62.9	207.4	3.3	65.5	1196.5	18.3
1.30 × 1.38	16.9	8.8	148.7	79.8	356.1	4.5	37.1	1085.7	29.3
1.38 × 1.50	5.4	16.9	91.3	85.2	447.4	5.3	20.2	937.0	46.4
1.50 × 1.70	3.3	30.6	101.0	88.5	548.4	6.2	14.8	845.7	57.1
1.70 × 1.90	3.0	46.2	138.6	91.5	687.0	7.5	11.5	744.7	64.8
Sink 1.90	8.5	71.3	606.1	100.0	1293.1	12.9	8.5	606.1	71.3

Source: Reference 15

Figure 10. Washability Curves and Float-Sink Data

gravity within a specified amount (± 0.10 s.g. units in Figure 9) of the separating fluid. The quantity of near-gravity material provides an indication of the difficulty of separation.

As indicated by the discussion in Section 2.3, the ability to remove sulfur and various trace elements from raw coal will depend on the association of the trace elements with the minerals versus macerals. Coals containing fine-grained minerals dispersed throughout the coal will be much more difficult to clean than a coal in which the minerals occur as distinct, macroscopic components of the raw coal. Similarly, coals containing a high percentage of free swelling clays will be difficult to clean due to the excessive production of fines and materials having a lower apparent specific gravity than actually occurs in the raw coal. In both of these cases, coal washability tests are likely to indicate the potential for a high percentage of near-gravity material and the absence of a clear division between coal and mineral matter during cleaning.

Although the sulfur and trace element concentration in coal is reduced for most elements during cleaning, the concentration of these elements in the mineral refuse is correspondingly increased. A major environmental concern thus becomes the disposal of the refuse. An important consideration in evaluating the potential adverse impacts from disposal is the relative abundance of acid-forming minerals (those containing iron and manganese) in the waste. When the acid-forming minerals are abundant relative to the alkali minerals (those containing calcium, magnesium, and sodium), trace elements in the refuse are likely to be leached and present a water quality problem. Leaching of coal preparation plant refuse is discussed in Section 3.4.

3.1.3 Major Pollutant Streams

The major feed, product, and waste streams associated with a coal preparation plant are:

- raw coal,

- cleaned coal,
- coarse and fine refuse,
- leachate streams from each of these solid streams,
- process water, and
- atmospheric emissions.

The relative and absolute size of each of these streams will vary based upon the design and size of the plant, the type of coal, and other factors. For a "typical" plant, an estimate of these splits would be that roughly 75 percent of the raw coal is produced as a cleaned product, 10-15 percent becomes a coarse refuse, 5-10 percent is fine refuse, and the balance is divided among the remaining streams. Current environmental regulations often require that process waters be recirculated within the plant such that there is zero discharge of process waters from the plant.

Another measure of the importance of these process streams is the projected environmental significance of the individual streams. A method used in several studies (9-11) for making this assessment has been the Multimedia Environmental Goals (MEGs) developed by EPA (14). MEGs provide a comparative measure of the concentration levels at which exposure to various contaminants are believed injurious to surrounding populations and ecosystems. Both short-term and continuous exposure limits have been developed. The Discharge Severity (DS) for each contaminant in a waste stream can be determined by dividing the measured concentration of the contaminant by its corresponding MEG value. The Total Discharge Severity (TDS) for the waste stream can then be estimated by adding the DS value for each contaminant in the stream.

Using this TDS methodology criteria, Buroff (9, 10) and Miller (11) evaluated the waste streams from two preparation plants located in the eastern U.S. Both of the Buroff studies analyzed for the 10 major inorganic

elements found in coal ash plus 63 trace elements. Miller tested for four major elements (Fe, Mg, Mn, and Ca) and 14 trace elements (Sb, As, Ba, Be, B, Cd, Cr, Cu, Pb, Hg, Ni, Se, Tl, and Zn). Each of the studies identified the coarse refuse, fine refuse slurry, and sediments from the process water settling ponds to be of greatest environmental significance. Leachate and process waters from the cleaning plant and the raw coal, cleaned coal, and refuse storage piles were of secondary importance. Atmospheric emissions were of the least significance. Table 16 summarizes the findings of each of these studies with regard to the most significant streams. The metals of greatest significance were Fe, Mn, and Cr. The significantly higher TDS levels in the Miller survey are due to substantially higher levels of iron in the original coal.

In general, the TDS of the leachate associated with each of the identified solid wastes were a factor of 100 or more lower than for the solid. At pH levels less than 5.0, however, high trace element concentrations can occur. Table 17 presents data on the trace element concentration in acid drainage from refuse piles at 16 cleaning plants. DMEG values for trace elements in water are presented for comparison. These same studies found trace element levels for plant's having alkaline drainage to generally be 50 to 100 times lower than in acid drainage. The low TDS values for the leachates collected in the Buroff and Miller studies may in part reflect the effectiveness of existing pH controls used to reduce trace element mobility.

3.1.4 Partitioning of Sulfur and Trace Elements

Sulfur and trace elements are not eliminated through chemical conversion or other means during coal cleaning, but rather are simply redistributed between the cleaned coal and the refuse. During the last half of the 1970s, a number of research programs examined the redistribution of sulfur and trace elements in coal (2, 5-8, 12). Sections 3.1.4.1 and 3.1.4.2 review this earlier work on sulfur and trace elements, respectively. Section 4.1 presents the results of analysis conducted under the present study to consolidate and statistically evaluate the existing data for relationships of importance to elemental partitioning.

TABLE 16. SUMMARY OF TOTAL DISCHARGE SEVERITY (TDS) VALUES FOR THREE COAL PREPARATION PLANTS

Study	Plant Location	Coal Type	Waste Streams in Descending Order of Public Health (H) and Ecological (E) TDS Values ¹	Major Elements Contributing to TDS (DS ₁₀₀) ¹
Buroff, 1981a (Ref. 8)	W. Kentucky	Kentucky #9 and #11	Process Water Pond #1 Sediments	H-2,300 E-10,000 H-Sr, Mn, Fe, Cr; E-P
			Process Water Pond #3 Sediments	1,100 H-Fe, Mn; E-P
			Coarse Refuse	10,000 H-Fe, Mn, Cr; E-P
			Fine Refuse	900 H-Fe, Mn, Cr; E-P
			Process Water Pond #2 Sediments	1,100 H-Fe, Mn, Ba; E-P
Buroff, 1981b (Ref. 9)	So. Illinois	Illinois #6	Coarse Refuse	H-2,400 E-10,000 H-Mn, Pb, Fe, Se; E-P
			Desilting Pond Sediment	1,900 H-Mn, Fe, Ba; E-P
			Transformer Pond Sediment	1,500 H-Fe, Cr, Mn; E-P
			Fine Refuse	820 H-Fe, Cr, Mn; E-P
			Runoff Pond Sediment	760 H-Mn, Fe, B; E-P
			Transfer Pond Filtered Solids	410 H-Hg; E-P
Miller, 1981 (Ref. 10)	W. Kentucky	Kentucky #11	Coarse Refuse	H-40,600 E-2,500 H-Fe, Mn, Cr, Ni, Pb; E-Fe
			Process Water Pond #1 Sediments	16,900 H-Fe, Mn, Cr, Ni, Pb; E-Fe
			Fine Refuse	10,300 H-Fe, Mn, Cr, Ni, Pb; E-Fe

¹Modified for iron (Fe) with a Health MEG = 3 µg/g and Ecological MEG = 50 µg/g.

TABLE 17. TRACE-ELEMENT CONCENTRATIONS IN ACID DRAINAGE FROM REFUSE PILES

State	Preparation - Plant/Mine Sites																Water DMEG		
	PA	PA	PA	PA	P-Anth	P-Anth	PW	PW	PW	WV	WV	WV	WV	OH	OH	KY	IN	Health	Ecology
Mine Number	54	17	-	36	P1	P2	9	12	43	W-2	W-5	10	41	-	K-1	IN-3			
Parameter																			
pH	2.8	3.1	2.2	2.6	3.0	4.1	2.7	3.3	4.7	4.9	3.1	2.6	2.8	2.7	3.8	2.4			
Aluminum, mg/l	255	6.9	220	800	87	50	184	29	2.0	3.6	20	77	470	33.5	70	340			
Arsenic, µg/l	<30	<30	140	1300	--	--	<30	21	5.3	--	--	410	<30	<30	--	--	80	1	
Beryllium, µg/l	--	--	--	300	--	--	--	--	5.9	--	--	--	--	--	--	--	250	50	
Boron, mg/l	--	--	--	320	--	--	--	--	760	--	--	--	--	--	--	--	30	55	
Cadmium, µg/l	<4.0	<4.0	<4.0	22	--	--	20	<4.0	<5.0	--	--	88	<4.0	<4.0	--	--	47	25	
Calcium, mg/l	--	--	--	345	340	180	--	--	500	415	310	--	--	--	74	350	50	1	
Chromium, µg/l	<10	<10	550	370	--	--	10	22	<50	--	--	590	180	300	--	--	24	16	
Copper, µg/l	950	<10	640	1400	140	180	30	17	40	--	--	1000	240	200	--	160	5000	50	
Iron, mg/l	174	235	1743	9100	30	0.6	243	449	1.87	260	120	1931	190	144	2.5	2600	1.5	.25	
Lead, µg/l	<30	<30	<30	<100	--	--	<30	<5	<100	--	--	<30	<30	<30	--	300	250	50	
Magnesium, mg/l	240	142	148	575	250	140	184	160	430	146	230	215	--	43	85	285	90	87	
Manganese, mg/l	45.5	20.2	112	83	50	90	185	14.0	27.6	9	25	53	30.5	5.3	8.1	120	.25	0.1	
Mercury, µg/l	<0.2	0.36	2.6	0.26	--	--	<1.0	<0.2	0.96	--	--	<0.4	<0.2	--	--	--	10	250	
Nickel, mg/l	2.7	.32	4.1	12.2	1.7	1.1	2.1	<.01	.67	--	1.0	14.0	6.2	0.22	0.25	1.6	230	10	
Selenium, µg/l	<10	<10	<10	9.0	--	--	<10	<10	<5.0	--	--	170	80	40	--	--	50	25	
Zinc, mg/l	3.0	.557	11.0	31.0	2.8	2.4	3.7	.318	.80	0.2	1.5	23.0	10.0	.49	1.1	7.2	25	0.1	

Source: Reference 13

3.1.4.1 Sulfur

The removal of sulfur by coal washing was analyzed by Cavallaro et al. (1) in a study of 455 raw coal samples from throughout the U.S. Roughly one-half of these coals were taken from producing mines in the Northern Appalachian Region and the balance were selected from throughout the rest of the major U.S. coal regions. More detailed studies on the coals of Pennsylvania (16) and Ohio (17) have also been conducted and studies for West Virginia and the Western U.S. are underway (18). These studies have included standard washability tests to determine sulfur removal potential for each sample as a function of specific gravity of the separation fluid and size of the raw coal feed. Reported data for each sample are as shown in Table 18 for a sample from the Upper Freeport seam in Indiana County, Pennsylvania.

In this example, the raw coal contained 13,150 Btu/lb (30.5 MJ/kg) (moisture-free basis; variations in values between individual size fractions reflect the inherent heterogeneity of coal), 15.4 percent ash, 1.2 percent pyritic sulfur, 1.7 percent total sulfur, and would have resulted in an uncontrolled emission from combustion of 2.6 lbs of SO₂ per million Btu (1.12 g/MJ). Cleaning the 3/8 inch (9.5 mm) sample at a s.g.=1.6 resulted in recovery of 83.9 percent of the total weight and 93.1 percent of the heating content; improved the Btu/lb to 14,614 (33.9 MJ/kg); decreased ash, pyritic sulfur, and total sulfur to 6.1 percent, 0.42 percent and 0.97 percent, respectively; and decreased SO₂ emissions per million Btu to 1.3 lbs (0.56 g/MJ). In order to reduce the SO₂ emission to 1.2 lbs per million Btu (0.52 g/MJ) (the regulated standard for certain coal-fired electric utility and large industrial boilers), the 3/8 inch (9.5 mm) sample would need to be floated at slightly less than s.g.=1.4, resulting in 78.2 percent weight recovery, 87.8 percent Btu recovery, a heat content of 14,789 Btu/lb (34.3 MJ/kg) ash of 5.0 percent, pyritic sulfur of 0.34 percent, and total sulfur of 0.89 percent.

Cavallaro et al. (1) present average sulfur and ash removal values for six major regions plus seven coal beds within the Northern Appalachian Region and ten coal beds in the eastern portion of the Interior Province. As shown in Figure 11, grinding coal to finer sizes liberates an increased percentage of the mineral matter in most coals, thereby improving cleanability. No

TABLE 18. EXAMPLE WASHABILITY DATA FOR AN UPPER FREEPORT
COAL FROM INDIANA COUNTY, PENNSYLVANIA

STATE: PA. (BITUMINOUS)

COUNTY: INDIANA

COALBED: UPPER FREEPORT

RAW COAL MOISTURE: .5 %

CUMULATIVE WASHABILITY DATA

SAMPLE CRUSHED TO PASS 1-1/2 INCHES

PRODUCT	RECOVERY %		BTU/LB	ASH %	SULFUR %		LB SO2/M BTU
	WEIGHT	BTU			PYRITIC	TOTAL	
FLOAT-1.30	49.9	56.9	14987	3.7	.21	.74	1.0
FLOAT-1.40	78.0	86.9	14629	6.0	.51	1.06	1.4
FLOAT-1.60	85.0	93.4	14427	7.3	.65	1.19	1.6
FLOAT-1.90	88.6	95.9	14225	8.6	.75	1.29	1.8
TOTAL	100.0	100.0	13135	15.6	1.22	1.71	2.6
EPA STANDARD	64.9	73.3	14822	4.6	.34	.89	1.20

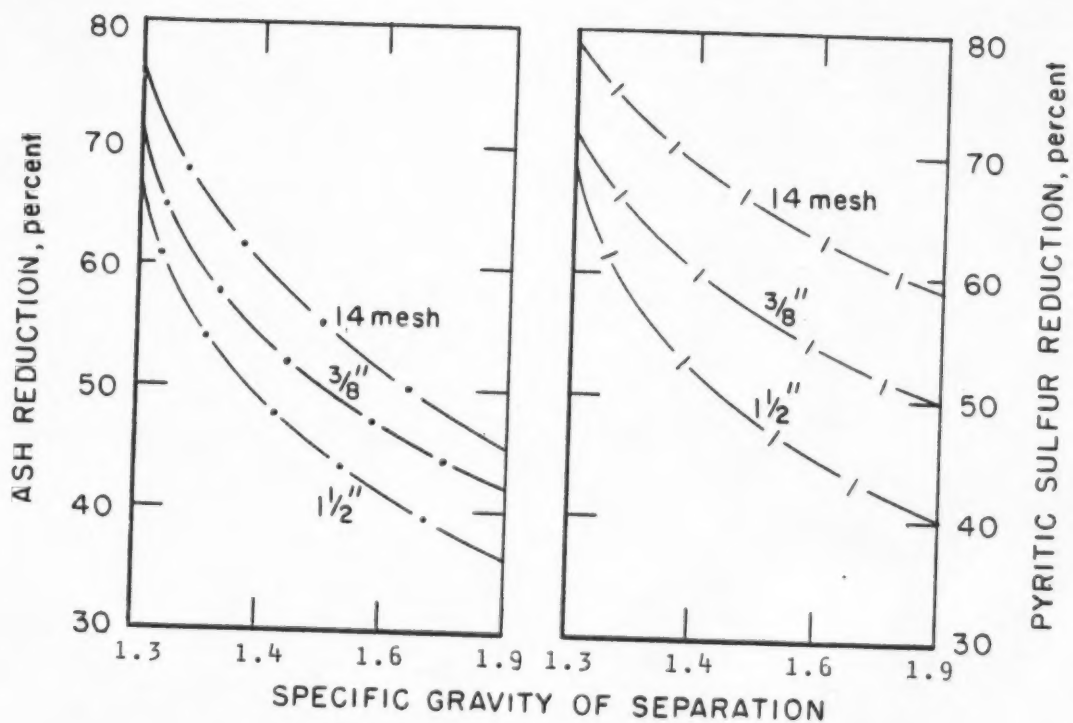
SAMPLE CRUSHED TO PASS 3/8 INCH

PRODUCT	RECOVERY %		BTU/LB	ASH %	SULFUR %		LB SO2/M BTU
	WEIGHT	BTU			PYRITIC	TOTAL	
FLOAT-1.30	61.7	70.3	15003	3.6	.20	.74	1.0
FLOAT-1.40	78.4	88.0	14785	5.0	.34	.89	1.2
FLOAT-1.60	83.9	93.1	14614	6.1	.42	.97	1.3
FLOAT-1.90	87.6	95.9	14411	7.4	.49	1.03	1.4
TOTAL	100.0	100.0	13166	15.4	1.13	1.64	2.5
EPA STANDARD	78.2	87.8	14789	5.0	.34	.89	1.20

SAMPLE CRUSHED TO PASS 14 MESH

PRODUCT	RECOVERY %		BTU/LB	ASH %	SULFUR %		LB SO2/M BTU
	WEIGHT	BTU			PYRITIC	TOTAL	
FLOAT-1.30	51.7	59.1	15081	3.1	.13	.67	.9
FLOAT-1.40	77.3	86.6	14785	5.0	.27	.81	1.1
FLOAT-1.60	84.4	93.4	14598	6.2	.34	.88	1.2
FLOAT-1.90	88.0	96.1	14411	7.4	.40	.93	1.3
TOTAL	100.0	100.0	13198	15.2	1.20	1.71	2.6
EPA STANDARD	84.1	93.1	14608	6.1	.34	.88	1.20

Source: Reference 1



Source: Reference 1

Figure 11. Effect of Crushing on Ash and Pyritic Sulfur Reduction at Various Specific Gravities of Separation for 455 U.S. Coal Samples

effort was made to describe the mineralogy or petrology of the coals or their roles in sulfur removal. Likewise, variations in sulfur removal as a function of cleaning technologies were not examined.

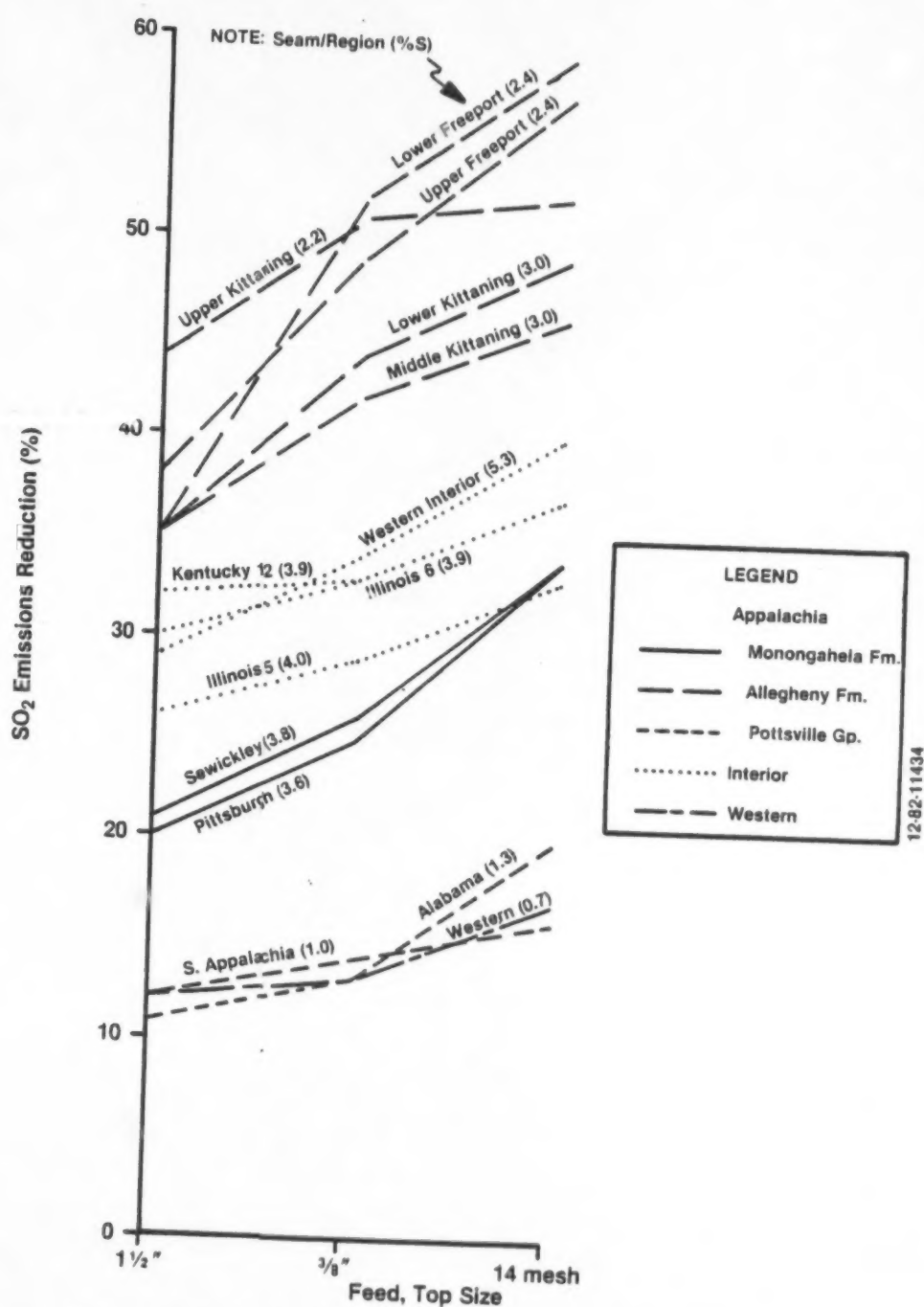
General conclusions obtained by these studies are that ash and sulfur contents can be reduced for essentially all coals by PCC; general correlations exist between the amount of ash and pyritic sulfur in the raw coal and the level of removal possible. A regional summary for sulfur and ash reduction is presented in Table 19. Based on this table the potential for total sulfur reduction is generally greatest in the northern Appalachian region and the Interior province and lowest in southern Appalachia, Alabama, and the western U.S. Similar regional trends also exist for ash, but are less distinct. Sulfur reduction data for selected regions and major seams are presented in Figure 12.

On a regional and seam-wide basis, Figure 12 indicates significant similarities in coal washability for seams having similar geologic and chemical characteristics. For example, excluding the Allegheny Formation coals, all coals show a greater improvement in cleanability by grinding from 3/8 inch (9.5 mm) to 14 mesh (1.18 mm) than from 1-1/2 inch (38.1 mm) to 3/8 inch (9.5 mm). The Allegheny coals, however, show a greater improvement in cleanability with size reduction from 1-1/2 inch (38.1 mm) to 3/8 inch (9.5 mm) than by further grinding to 14 mesh (1/18 mm). Also, the sulfur reduction level compared to the total percent sulfur is higher for the Allegheny coals than for other coals. This is explained in part by the higher percentage of pyritic sulfur found in the Allegheny coals, and may also indicate that the size of pyrites in these coals is larger, and thus more readily separable than in other coals. From a depositional history perspective, this suggests that the Allegheny coals may have formed under geologic conditions which resulted in relatively low levels of syngenetic sulfur fixation, followed by precipitation of significant amounts of coarse-grained epigenetic pyrite.

TABLE 19. SULFUR REDUCTION POTENTIAL FOR 455 U.S. COALS BY REGION (1.60 float, 3/8" x 0" size)

Region	N	Total Sulfur Content (%) (Mean; %)	Total Sulfur Reduction (%) (Mean±Std dev; %)	Pyritic Sulfur Content (Mean; %)	Pyritic Sulfur Reduction (Mean±Std dev; %)	Ash Content (Mean; %)	Ash Reduction (Mean±Std dev; %)
Northern Appalachia	227	2.99	34 ± 20	1.99	55 ± 20	15.1	43 ± 17
Southern Appalachia	35	1.04	8 ± 12	0.37	39 ± 23	11.0	45 ± 21
Alabama	10	1.32	9 ± 8	0.68	31 ± 19	9.4	37 ± 21
Eastern Interior	95	3.89	28 ± 13	2.27	51 ± 17	14.1	38 ± 17
Western Interior	44	5.19	28 ± 14	3.53	46 ± 17	16.0	45 ± 13
West	44	0.67	10 ± 17	0.23	34 ± 26	9.0	26 ± 14
Total	455	2.98	27 ± 20	1.88	50 ± 21	14.0	42 ± 17

Source: Reference 1



Source: Reference 1

Figure 12. Coal Cleaning SO₂ Emissions Reduction Percentages for Selected Coals and Feed Sizes

3.1.4.2 Trace Elements

The removal of trace elements from coal during coal cleaning has been examined both in laboratory washability studies and in analyses of operating preparation plants. DOE (2), ISGS (5), and BCR (7,8) have analyzed 45 coals using laboratory washability tests. Table 18 provides descriptive information on these coals. BCR (7) also conducted trace element tests for six actual plants. Buroff (9, 10) and Miller (11) present data on removal of trace elements at three coal cleaning plants, but do not provide material balances.

Gluskoter, et al. (5) conducted laboratory washability tests on nine coals: five from Illinois, three from Appalachia, and one from Arizona. Tests were run on samples ground to 3/8 inch x 28 mesh (9.5 mm x 0.60 mm) using a separating fluid of perchloroethylene and naptha at s.g.=1.29, 1.33, 1.40, and 1.60. Each fraction was analyzed for proximate and ultimate composition, sulfur forms, major ash chemistry, and up to 43 trace elements. These data were then used to compute "organic affinity" values as discussed in Section 2.3.1.

Cavallaro, et al. (2) examined the trace element reduction potential for ten coals (four eastern, three Interior, and three western) and eight trace elements (Cd, Cr, Cu, F, Hg, Mn, Ni, and Pb). Gravity separations were made for 14 mesh (1.18 mm) x 0 coal at s.g.=1.3, 1.4, and 1.6 using CERTIGRAV, a commercial organic liquid. The results of the washability tests at s.g.=1.6 are presented in Table 20 by region. These data indicate that significant variations in trace element reduction potential exist in the regional averages. Trends in the data, however, are in general agreement with the organic affinity data presented in Table 11. That is, elements with low organic affinity indices have a greater reduction potential, and vice versa. Material balances for the ten coals tested ranged from 85 to 115 percent with an average of 99 percent and a 95-percent confidence interval of 3 percent. In addition to the trace element data, each gravity split was analyzed for ash, total sulfur, and pyritic sulfur (these data are not provided in the report). Major element chemistry of the ash was not determined (17).

TABLE 20. TRACE ELEMENT REDUCTION POTENTIAL FOR EIGHT ELEMENTS AND
TEN COALS BY REGION

	N	Cd	Cr	Cu	F	Hg	Mn	Ni	Pb	Ave.
East	4	21	26	33	44	44	51	25	52	37
Interior	3	88	8	21	11	22	72	2	34	32
West	<u>3</u>	<u>30</u>	<u>3</u>	<u>12</u>	<u>20</u>	<u>33</u>	<u>64</u>	<u>2</u>	<u>28</u>	<u>24</u>
Total	10	44	14	23	27	34	61	11	39	32

Source: Reference 2

Studies of the trace element removal potential have been conducted by Bituminous Coal Research, Inc. (BCR) (6, 7) on a total of 26 coals. Of these, 20 coals were tested solely under laboratory conditions with the remaining six evaluated in operating commercial coal cleaning plants as well as under laboratory conditions. Most separations were made at s.g.=1.35, 1.55, and 1.80 using a magnetite heavy-media device and size fractions of 1-1/4 inch x 1/4 inch (31.8 mm x 6.4 mm), 1/4 inch x 30 mesh (6.4 mm x 0.53 mm), and 30 mesh x 0 (0.53 mm x 0). The results obtained by BCR from the laboratory testing are summarized in Table 21. In comparison to Table 20, these values show generally better trace element removal potential for eastern and interior coals and lower values for western coals. Of the more than 5,000 individual material balances conducted during this study, roughly 95 percent were within ± 25 percent of closure.

In addition to percentage reduction estimates, BCR also examined the data for correlations between trace elements and other coal properties, including petrographic constituents; leachability of trace elements from raw coal, cleaned coal, and refuse; and differences in trace element removal ability of alternate cleaning methods. Major findings of the BCR studies are:

1. Trace element reduction potential estimated from laboratory analyses are generally comparable to those obtained from commercial coal cleaning plants.
2. The variability in trace element reduction potential for two coals from different locations within the same seam is as great as it is for coals taken from different seams.
3. The trace element reduction potential of a given coal is related to the amount of ash in the coal; i.e. a low ash coal will have a lower trace element reduction potential than a high ash coal, even if the two fuels come from the same seam.
4. Petrographic information on a coal is of little value in determining trace element reduction potential.

TABLE 21. TRACE ELEMENT REDUCTION POTENTIAL FOR 16 ELEMENTS AND 26 COALS BY REGION

	N	As	B	Be	Cd	Co	Cr	Cu	F	Hg	Mn	Ni	Pb	Sb	Se	V	Zn	Ave.
East	16	60	37 ¹	27	41	39 ²	53	44	60	34	71	38	58	19 ⁴	35	49	59	45
Interior	5	51	17 ³	22	78	51 ¹	49	50	57	16	72	46	57	6 ⁴	35	35	72	44
West	1	47	ND ⁴	-1	25	ND ⁴	17	12	13	23	24	6 ⁴	33	35	23	4	10	20
Total	26	56	30	21	45	42	45	39	50	28	62	33	53	21	33	38	52	40

¹4 Samples

²2 Samples

³12 Samples

⁴10 Samples

⁵3 Samples

⁶No data

Source: References 6 and 7

5. Statistically significant correlations exist between the trace element reduction potential for Be, Cr, Cu, F, Pb, Mn, Ni, V, and Zn and the levels of major elements in the coal.

3.1.5 Summary and Conclusions

3.1.5.1 Environmental Significance of Sulfur and Trace Elements in Coal Preparation

Except where acidic conditions exist, environmental impacts from sulfur and trace element emissions during coal preparation activities are generally small compared to other coal utilization technologies. Further, existing technology for controlling the runoff and acidity of leachate and liquid effluents from coal preparation plants appears capable of minimizing impacts from acidic coals and refuse. Leaching is further discussed in Section 3.4. Where impacts do occur, they are generally confined to the area proximate to the cleaning facilities.

Given this situation, the major environmental issue relative to sulfur and trace elements from coal preparation is the enrichment of these elements in cleaned coal which is subsequently burned or converted to another energy form. These impacts are discussed in the following two sections on combustion (Section 3.2) and synthetic fuels (Section 3.3).

Existing knowledge of the partitioning of sulfur and trace elements during cleaning is largely empirical, as is true of coal cleaning technology in general. Several studies (1, 7, 8) have included coal washability tests to determine trace element reduction potentials. Substantially more information is available with regard to sulfur, but the ability to predict sulfur reduction based on specific coal properties is currently limited and is largely based on experience rather than on theoretical considerations.

A logical next step in the process of better understanding trace element removal potential for specific coals is to further assess the existing data using various statistical methods. Initial efforts in this regard have been

made by BCR (7) based on a sample of 20 coals. Additional data are available from DOE, ISGS, and other sources (see Table 18) which could be used to expand on BCR's earlier efforts. To the extent that partitioning can be predicted based on knowledge of the chemical characteristics of a coal, this approach may be useful. However, given the high degree of variability in coal, the ability to develop a partitioning methodology based on commonly available coal analyses is subject to significant uncertainty.

3.1.5.2 Existing Knowledge on the Effect of Coal Properties on Sulfur and Trace Element Partitioning

The chemical and mineralogical properties of coal have a significant impact on the potential for removal of sulfur and trace elements by coal washing. Specific coal properties of importance include whether an element occurs 1) in conjunction with the high specific gravity pyrites, the medium density clays and carbonates, or the lighter organic matrix; and 2) as macroscopic crystals or agglomerates, as fine grained minerals distributed throughout the coal, or as organically bound molecules. For example, the removal of sulfur from the coal depends on whether the sulfur is present in the coal as pyrite, as a fine-grained trace element sulfide such as galena or sphalerite, as an organically bound molecule, or as a sulfate. Most of the discussion in Section 2 regarding the mode of occurrence for trace elements and sulfur in coal is directly applicable to understanding of how coal properties influence both physical and chemical coal cleaning processes.

Section 4.1 presents a statistical evaluation of existing data developed by ISGS, DOE, and BCR. The primary focus of these results is on the relationship between the trace elements and sulfur versus the major minerals in coal.

3.2 COMBUSTION

3.2.1 Introduction

Direct combustion is currently the primary use of coal in the U.S. Most coal is pulverized and fired in large boilers, although a significant percentage is also stoker-fired in smaller industrial and commercial burners. The fate of sulfur and trace elements in such uses is the subject of this section.

Dry coal generally contains from 5 to 25 percent by weight of elements other than carbon, hydrogen, and oxygen. Any of these other elements may be considered as potential pollutants. Nitrogen oxide by-products, arising from both organically bound nitrogen and fixation of atmospheric nitrogen, are not within the scope of the present study. In general, nearly all the non-sulfate sulfur in the coal is converted to SO_2 and a few percent to SO_3 . Minor and trace elements experience a variety of fates. Some are melted and included in the aluminosilicate matrix which forms the major structure of coal fly ash, others fall to the base of the boiler as bottom ash or slag, and still others are vaporized and oxidized. The volatile elements may subsequently condense onto the available surfaces (mostly fly ash particles) or be vented as vapors. Nearly all trace elements become enriched in the ash since most of the mass (i.e., the carbon) has burned away. For sulfur and most trace elements, the nature of the combustion and cooling processes (i.e., temperature profiles, residence time, amount of excess oxygen) is recognized as being more important in determining the final form of the element than its structure or form in the original coal.

Although there is a general understanding of the major processes of fossil fuel combustion, individual studies have differed considerably in quality and completeness of data, area of emphasis, methods used, types of systems studied, etc. Generalized conclusions drawn from a comparison of different studies are frequently difficult to make. While not ignoring nor excluding any reports a priori, the present work, in order to determine partitioning

and enrichment factors, has relied principally on projects wherein mass balances around the combustion process were included as one objective of the study. In each of these efforts, all incoming and outgoing streams were quantified, and the percent of closure is representative of the quality and reliability of the measurements; such information is particularly useful in individual elements. Also, only studies using atomic absorption (AA), neutron activation analysis (NAA), X-ray fluorescence (XRF), isotope dilution-mass spectrometry (ID-MS), or multiple analytical methods for elemental determinations were considered sufficiently reliable and accurate for inclusion in the general tables. Fifteen such studies were identified in the literature survey and used in this report.

Mass balance studies quantify all incoming and outgoing streams around the combustion facility. The incoming streams are the fuel itself, air (which is usually considered to contain no trace elements), and sluicing waters. The outgoing pathways, for the purposes of this study, have been lumped into the bottom ash or slag, fly ash (including all gaseous and particulate matter leaving the top of the boiler minus that emitted into the atmosphere), and atmospheric emissions (including vapors and fine particles passing the particulate control device). It is uncommon to find trace element analysis of the actual vapors.

Because each plant and each process are unique, the partitioning of trace elements through a particular plant, combustor, and pollution control device will result in plant specific data which are not easily generalized to a non-specific basis for interplant comparisons. The effect of various process and control devices on trace metal distribution is qualitatively recognized in this study but is not quantified.

3.2.2 Combustion Processes

In large industrial and utility boilers, coal is crushed or pulverized into a powder (200 mesh, 75 μ m) and blown into a large firebox with air. Combustion is rapid (within a few seconds) and complete (99 percent plus). Combustion temperatures are 1000-1500°C. In smaller industrial and commercial

uses, coal is usually fired on a bed or grate. The coal is sized in lumps typically 1-5 centimeters across. Air is passed through the coal bed and combustion is slow (minutes to hours) and at relatively low temperatures (below 1000°C).

In the smaller systems, particle heating is slow, typically something like 1°C/sec. Because of this, the coal lump does not usually thermally shatter, and the organic species are slowly decomposed (cracked) and pyrolyzed away (20). Because of the relatively low maximum temperature, many of the minerals in the coal remain intact. The percentage of ash that becomes entrained with the flue gas is dependent upon the process conditions (e.g., lump size, velocity of air through bed). Although different studies vary on the percentage of entrainment, many bed systems are designed to retain a large percentage of the ash; see Tables 22 and 23 and reference 23. Trace element emission characteristics of these boilers have not been studied extensively. One study of a stoker boiler did report trace element concentrations in the coal (ash), bottom ash, and fly ash (24). Even in systems which reach only 1000°C, sulfur is assumed to be totally oxidized to SO₂ and SO₃ except for mineral sulfates; also small amounts of SO_x may be captured by the ash. See below for further discussion of sulfur and ash.

In pulverized coal combustion systems, temperatures are typically 1300°F or greater, and the particles are very rapidly heated (10³-10⁶ °C/sec). The volatile organic species are quickly vaporized and evolved from the solid particle. The pyrolysis step is complete in less than 20 μsec (25). During this time, the vapor flush will keep the actual combustion surface at some (stand off) distance from the heterogeneous surface of the particle. The particle will be in a reducing atmosphere until the pyrolysis is essentially complete. For larger particles, the remaining char will then burn out approximately according to the Nusselt square-law relationship (26):

$$t = 10^{-5} d^2, \text{ for } d > 100 \mu\text{m},$$

where d is the particle diameter in μm and t is the particle burn-out time in seconds. As the particle is rapidly heated and burns, it will fragment into

TABLE 22. COMPARISON OF DISTRIBUTION BETWEEN BOTTOM ASH AND FLY ASH BY TYPE OF BOILERS AND METHOD OF FIRING

Type of Bottom Boiler	Type of Firing*	Percent Bottom Ash	Percent Fly Ash
wet	PCFR	35	65
wet	PCOP	35	65
wet	PCTA	35	65
dry	PCFR	15	85
dry	PCOP	15	85
dry	PCTA	15	85
--	CYCL	90	10
--	SPRE	35	65

*PCFR - Pulverized coal front firing
 PCOP - Pulverized coal opposed firing
 PCTA - Pulverized coal tangential firing
 SPRE - Spreader stoker

Source: Reference 21

TABLE 23. DISTRIBUTION OF COAL ASH FROM VARIOUS FURNACE CONFIGURATIONS

Furnace	Percent Bottom Ash	Percent Boiler Slag	Percent Fly Ash
Stoker fired - traveling	100	--	--
Stoker fired - spreader	--	45-85	15-55
Cyclone fired	--	80-85	15-20
Pulverized coal - wet bottom	50	--	50
Pulverized coal - dry bottom	20-25	--	75-80

Source: Reference 22

smaller pieces, typically 5 to 10 pieces per original particle (27). Eventually all the carbon is oxidized to CO_2 (with small amounts of CO) and the nitrogen to NO (with small amounts of NO_2).

3.2.3 Major Pollutant Streams

In any combustion facility, the by-products create several waste streams. Different plants with different processes generate separate varieties of waste. The combined vapors (other than SO_2 and NO_x) and fly ash particles passing a modern particulate control device (e.g., ESP, baghouse, wet venturi) appear to have (with the possible exception of Hg) little or no adverse environmental impact in the immediate area of the plant (28-30). However, the smaller particles (less than 2 microns) are suspected to be of general concern to humans and other air-breathing animals since they may penetrate deep into the lungs and are usually enriched in trace elements (31).

The disposal of bulk solids can impact the environment via leaching of the trace elements from the ash. The various solid waste streams associated with coal combustion are defined and described below. The leaching of coal combustion solid wastes is dealt with in Section 3.4.

Depending on boiler design, some of the minerals resulting from combustion may be deposited in the bottom of the boiler. If the bottom material is melted (due to either a high temperature boiler or a low melting ash), slag is the product. If the bottom material is "dry" (i.e., not liquid), it is called bottom ash. Either product may be removed and disposed of as is, but in utility boilers, bottom ash is usually sluiced to a collection pond. The sluice water will leach some species from ash and may result in a hazardous material; such waters are usually recycled through settling ponds. Waste stream characterizations (e.g., metal cation concentrations in ash sluice liquors) should not be confused nor directly compared with leaching studies, but disposal of the bottom product (be it sluice water, pond sediment, or dry landfill) is a necessity and can have an impact on the environment. Data from leaching studies of bottom material are given in Section 3.4.

Some boilers are designed to collect a high percentage of the total ash as bottom ash (e.g., cyclonic fired and stoker types), while other are designed to collect a much lower percentage of bottom ash (e.g., pulverized coal, wall fired); see Tables 21 and 22 for the results of two similar studies. Thus, both the volume and form of the bottom material may vary considerably from one boiler or process to another. There are hundreds of reports of trace element concentrations in ashes; Table 24 gives typical data and also serves to illustrate that the ash composition is highly dependent upon process conditions and types of pollution control devices as well as upon coal composition.

The material leaving the top of the boiler is first cooled by the economizer, which also collects the largest particles of fly ash. Economizer ash is often combined with bottom ash for handling and disposal. As the flue gas stream cools further, subsequent particle removal devices collect either a dry ash (e.g., ESPs and baghouses) or an aqueous slurry containing the fly ash (e.g., wet venturis or flue gas desulfurization (FGD) units). The dry ashes are often referred to as hopper ash. In modern pulverized coal systems, hopper ash makes up most of the solid waste materials. Dry ash is usually disposed of in a landfill or occasionally used as a construction base or filler. Environmental impact is usually via leaching from a landfill; data on several ashes are given in Section 3.4. However, site-specific factors usually are the principal determinants in the eventual environmental impact of the hopper ash.

Aqueous ash waste streams containing fly ash are usually "dewatered" at the site before ultimate disposal; the water removed is generally recycled resulting in zero discharge. The nature of the dewatered product is highly dependent upon its total composition. If it is principally dewatered fly ash (e.g., from a wet venturi scrubber or ash sluice), it will probably be similar to untreated fly ash except some leaching (or possible deposition from drying of sluice water) may have taken place. If so, its subsequent leaching characteristics may have been altered from those of the dry ash. If the waste is an FGD by-product, consisting largely of CaSO_3 , CaSO_4 , or MgSO_4 , and small to

TABLE 24. CONCENTRATIONS OF SELECTED TRACE ELEMENTS
IN AN INTERIOR PROVIDE COAL AND ASH (ppm)

Element	Coal ^a	Bottom Ash	Inlet Fly Ash ^b	Outlet Fly Ash ^c
As	4.45	18	110	440
Ba	65	500	465	750
Br	3.7	2	4	
Cd	0.47	1.1	8.0	51
Ce	8.2	84	84	120
Cl	914	<100	<200	
Co	2.9	20.8	39	65
Cr	18	152	300	900
Cs	1.1	7.7	13	27
Cu	8.3	20	140	
Eu	0.1	1.1	1.3	1.3
Ga	4.5	5	81	
Hf	0.4	4.6	4.1	5.0
Hg	0.122	0.028	0.050	
La	3.8	42	40	42
Mn	33.8	295	298	430
Ni	16	85	207	
Pb	4.9	6.2	80	650
Rb	15.5	102	155	55
Sb	0.5	0.64	12	36
Sc	2.2	20.8	26	88
Se	2.2	0.08	25	36
Sm	1.0	8.2	10.5	9
Sr	23	170	250	
Ta	0.11	0.95	1.4	1.8
Tn	2.1	15	20	26
U	2.18	14.9	30.1	
V	28.5	260	440	1180
Zn	46	100	740	5900

^aMixture of coals from southern Illinois and western Kentucky.
Ash content 12%. Pulverized coal firing.

^bCollected upstream from electrostatic precipitator.

^cCollected downstream from electrostatic precipitator.

Source: Reference 32.

large amounts of fly ash, the physical character of the waste may be very different from dry ash. FGD sludge may be ponded as a slurry or treated to form solid waste which may be disposed of by landfilling. Leaching data on FGD sludges are also given in Section 3.4. Table 25 gives data typical of wastes generated from an FGD system.

3.2.4 Partitioning Elements

3.2.4.1 Partitioning of Major and Minor Elements

In most commercial, industrial or utility boilers, essentially all of the carbon in the coal is burned and the remaining elements are converted to oxides and make up the ash. Generally the bottom ash and fly ash are similar in composition, with the more volatile elements and element oxides being enriched in the fly ash as shown in Table 24. Some sulfur present originally as sulfate may deposit in the bottom ash.

Depending upon the elemental composition of the coal, the major mass components of the ashes are the oxides of silicon, aluminum and iron. These ashes usually consist of mixtures of three phases. The dominant product is most frequently an aluminosilicate ($Al_xSi_yO_z$).

Usually occurring in lesser amounts are crystalline mullite-quartz (also an aluminosilicate) and magnetic spinel (a ferrite oxide) (34). Of these latter two compounds, the mullite-quartz is usually the more abundant species, sometimes accounting for up to 30 percent of the fly ash mass.

Other elements that frequently occur in amounts between 0.1 and 10 percent (i.e., the minor elements) are Ca, K, Mg, Na, Ti, and sometimes Ba, Mn, P and Sr. Trace elements are essentially all other elements, which usually occur in even smaller (<0.1%) amounts.

The flue gas is composed principally of N_2 (from the air), O_2 (from excess oxygen), CO_2 and H_2O (combustion by-products), some CO , SO_2 and NO_x (mostly NO with 1-10% NO_2). Small amounts of volatile elements (or element

TABLE 25. RANGE OF CONCENTRATIONS OF CHEMICAL CONSTITUENTS
IN FLUE GAS DESULFURIZATION SLUDGES

Scrubber Constituent	Sludge Concentration Range	
	Liquor, mg/l*	Solid, ppm**
Aluminum	0.03 - 1.0	---
Arsenic	<0.004 - 1.8	0.6 - 52
Beryllium	<0.002 - 0.18	0.05 - 6
Cadmium	0.004 - 0.11	0.08 - 4
Calcium	180 - 2,600	105,000 - 268,000
Chromium	0.015 - 0.5	10 - 250
Copper	<0.002 - 0.56	8 - 76
Lead	0.01 - 0.52	0.23 - 21
Magnesium	4.0 - 2,750	---
Mercury	0.0004 - 0.07	0.001 - 5
Potassium	5.9 - 100	---
Selenium	<0.0006 - 2.7	2 - 17
Sodium	10.0 - 29,000	(4.8)
Zinc	0.01 - 0.59	45 - 430
Chloride	420 - 33,000	(0.9)
Fluoride	0.6 - 58	---
Sulfate	600 - 35,000	35,000 - 473,000
Sulfite	0.9 - 3,500	1,600 - 302,000

* Liquor analyses were conducted on 13 samples from 7 power plants burning eastern or western coal and using lime, limestone, or double-alkali absorbents.

**Solids analyses were conducted on 6 samples from 6 power plants burning eastern or western coal and using lime, limestone, or double-alkali.

Source: Reference 33

oxides) may also be included in the off gases; see Section 3.2.4.3. Sb, As, Br, F, Hg, Se and sometimes Pb and Ni are also present.

3.2.4.2 Sulfur

Sulfur, which may be either a major or minor element, deserves special attention. Most of the sulfur entering a boiler leaves as SO_2 gas and is of primary environmental concern since the SO_2 will contribute to the formation of small particles (sulfates, which affect visibility) or acid rain.

The sulfur in the coal may be in three basic forms: organic, pyritic, and sulfate. In fresh coals, the concentration of sulfate is usually below 500 ppm (1); sulfate remains as sulfate during combustion. Unless combustion conditions are at either low temperature (below 1000°C) or no excess oxygen, organic and pyritic sulfur will be oxidized to SO_2 or SO_3 .

Thermodynamics predict that substantial amounts of SO_3 should be formed, but in practice, only about one percent of the flue gas sulfur is SO_3 (the rest being SO_2). Apparently the kinetics of the combustion process favor SO_2 , since even excess air does not affect the SO_2/SO_3 ratio. However, certain elements are known to catalyze (speed up) oxidation to SO_3 (e.g., oxides of iron, silicon, aluminum, vanadium) and fuels rich in such elements tend to produce more SO_3 , which is readily retained by the fly ash as sulfate (see below).

Production of SO_3 is important in sulfur control. Sulfur trioxide is very reactive and once the system has cooled to 150°F , it "sticks" to the first surface it encounters—usually a small fly ash particle. (Most of the surface area in a flue gas-fly ash stream is accounted for by the small ($<2\text{m}\mu$) particles.) The SO_3 either reacts directly with the basic metal oxides (e.g., $\text{CaO} + \text{SO}_3 \rightarrow \text{CaSO}_4$) or via water as a catalyst (e.g., $\text{SO}_3 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4 \xrightarrow{\text{CaO}} \text{CaSO}_4 + \text{H}_2\text{O}$) to form metallic sulfates. Some mineral forms of sulfur can theoretically withstand the combustion conditions (e.g., melting point of FeS_2 is 1180°C), but typically, few of the original coal-based sulfur minerals are found in fly ash.

The amount of sulfur retained by the ash is of interest as a possible means of SO₂ control. Sulfur retained by the ash exists as either sulfates (efficient sorption of SO₂) or sulfites (rather inefficient sorption of SO₂), mostly in association with alkaline oxides. Therefore, sulfur retention is mainly a function of how much SO₂ is produced and the alkalinity of the ash (37). As discussed in Section 2.1, low-rank coals tend to be both alkaline and low in sulfur; their flue gases are low in SO₂. Gaseous SO₂ is substantially higher for bituminous or subbituminous coals. Bituminous coals generally retain a smaller percentage of sulfur due to their more acidic ash character. One study which analyzed eight different ashes for sulfur reported 0 - 6.4% sulfur retention rate (35); another reported some western, high alkaline ashes to retain up to 20% of the sulfur (38). Yet another reported sulfur retention rates of 0.6 - 0.8% for the Eastern province, 0.4 - 1.2% for the interior province and 1.4 - 8.2% for Western states (39). Much of the sulfur deposition onto fly ash occurs as the gas is cooled, and the small particles are usually highly enriched in sulfur. For example, one study reported that the weight percent of sulfur increased from 8.3 to 48.8 percent as the particle diameter decreased from greater than 11 μ m to about 1 μ m (40).

At the present time, EPA is actively sponsoring research on the boiler injection of coal and SO₂ sorbents (principally calcium) to increase the alkalinity and sulfur retention of fly ash particles within the boiler. This dry SO₂ control process (EPA uses the acronym LIMB-Limestone Injection-Multistage Burning), which also is useful for decreasing NO_x production, has been demonstrated to increase sulfur retention (41-43).

3.2.4.3 Trace Elements

Trace metals may undergo several processes during coal combustion. Most of the metals intimately bound in the organic structure of the coal are quickly vaporized and oxidized. Mineral matter in the coal is melted to form a droplet as the coal particle is progressively vaporized, pyrolyzed, and oxidized. Some of the more volatile metals or metal oxides will diffuse to the

surface of the liquid droplet and be liberated, presumably resulting in their complete oxidation. The melted droplet will crust over as soon as the flue gas is cooled slightly or as the metals are oxidized (44).

Trace element concentrations among the three major ash phases mentioned above are shown in Table 26. In general, most of the alkaline earth, and lanthanide elements plus As, Se, Cd, Pb, Hg, and U are found amorphously trapped in the aluminosilicate glass. Mullite-quartz is generally low in trace elements except for V, Cr, and Ga which appear to occupy structural sites in the mullite crystal. Trace elements in the magnetic spinel phase include most of the first transition group elements (V, Cr, Mn, Co, Ni, Cu, and Zn) plus the rare-earths La and Ce. Of environmental significance, the elements found in the silicates have significantly lower leaching potentials in neutral waters than the elements found in the oxide spinel.

As mentioned above, certain elements or their oxides (or other possible species such as nickel carbonyl) have significant vapor pressures at typical stack temperature. Some portion of these elements may actually be emitted as vapors. The most abundant volatile trace element (sometimes classified as a minor element) emitted with the flue gas is Cl, with lesser amounts of other halogen elements, F and Br, also emitted. Other elements which are recognized to have a substantial (>10%) fraction in the vapor phase include Sb, As, Hg, Pb, Ni, Se; all of these species are of environmental concern. A few other trace elements sometimes detected in flue gas include B, Cd, Cr, and Mo. See Section 4.2 (particularly Tables 55 and 56) for more information on the fate of volatile trace elements.

In addition to these chemical differences between ash materials, there are also physical differences associated with the combustion process. Of primary importance is the effect of the combustion process on the size of ash droplets formed. For example, if the droplet is large, some species may not diffuse out of the droplet before the droplet surface begins to solidify, thus, the core material of larger fly ash particles will be richer in the volatile metals than the smaller particles. Conversely, most of the metals or metal oxides which are vaporized condense onto available surfaces as the flue

TABLE 26. ELEMENTAL DISTRIBUTION IN 100- to 200- μ m
SIZE FRACTION OF COAL FLY ASH (ppm)

Element	Glass	Mullite- Quartz	Magnetic Spinel
Al	87,200	204,000	86,600
Fe	19,600	3,400	605,000
Si	343,000	287,000	—
Na	1,710	256	2,080
K	25,000	5,270	3,590
Rb	532	12	229
Mg	10,400	15,500	0
Sr	798	174	0
Ba	319	69	0
Sc	31	7	15
Ti	10,900	4,630	0
V	176	127	150
Cr	169	311	1,380
Mn	87	9	1,040
Co	25	2	251
Ni	174	78	2,270
Cu	144	17	496
Zn	209	17	382
Ga	0	12	0
As	42	2	0
Se	54	7	38
Hg	8	1	0
Pb	35	2	—
La	61	0	14
Ce	119	6	141
Th	5	0	5
U	13	1	4

Source: Reference 45

gas is cooled. The smaller particles have a greater relative surface area than the larger particles, thus causing the surface of the smaller fly ash particles to become enriched in volatile metals.

These two opposite trends--volatiles enriched in the core of large particles and on the surfaces of small particles--lead to unclear results when fly ash particles are analyzed in bulk for trace elements according to size. To understand such results, the analytical process must be understood (e.g., some digestions do not dissolve the aluminosilicates, some are done at elevated temperatures causing the volatiles to be lost), the temperature and residence time in the combustion zone must be considered, and the temperature profile of the cooling process needs to be defined. In summary, the distribution of trace metals on fly ash particles, particularly by size, is highly variable and results vary markedly from study to study.

Collin (46) in Swaine (47) suggests that for conventional, spherical fly ash particles a three-layer structure exists: an inner core of metal oxides (basic), an intermediate shell (neutral), and an outer layer dominated by sulfates (acidic). A survey of the trace-metal-distribution-by-particle-size studies tends to show that the lower the temperature of vaporization of the metal oxide, the more likely that metal will be enriched in the small particle fractions. Apparently for these species, surface condensation on the small particles dominates the bulk phase diffusion enrichment mechanism. Section 3.2.4.3 presents data and further discussion concerning trace element distribution on fly ash particles of different size.

Quann et al. (48) have combusted pulverized coal in a bench top burner designed to simulate a utility boiler. They have found a bimodal size distribution which indicates that there are two distinct particle forming mechanisms. Particles larger than about 0.5 μm seem to result from the melting and fusing of mineral matter in the coal as described above. But they also found that particles smaller than 0.5 μm consisted of an entirely different chemical make-up, dominated by MgO (approximately 50%). They found that some of the major metals are vaporized from the coal particle in a reducing atmosphere (e.g., Mg vaporization temperature is 1105°C). However, after leaving the

particle, the metal vapors are quickly oxidized and are suddenly supersaturated in the vapor (e.g., MgO vaporization temperature is 3260°C). The oxides then rapidly and homogeneously condense into submicron particles. These new particles are highly enriched in Mg, Na, K, and P and severely depleted in Al and Si, which are the dominant metals in the larger particles. On top of this mechanism, the deposition of the metal oxides on available surfaces is also active, and these particles are additionally enriched in the more volatile trace elements. Quann et al. also observed that the submicron particles were subject to accretion and attachment to larger particles, thereby somewhat obscuring the mechanism to conventional particle size bulk analysis.

The effects of temperature on fly ash have also been studied. For example, assuming the gaseous sorption on fly ash is reversible, then heating the ash and monitoring the off-gases should mirror the deposition dynamics (49). When this was done, below 300°C water was desorbed; at 500°C, nearly all SO₂ and substantial amounts of CO₂ were desorbed. CO₂ continued to be released above 1000°C. Of the trace elements, Hg was 80% desorbed at 400°C; Se, Br, and I were released between 800-1200°C; and As was desorbed between 1200-1400°C. Significant amounts of Na, Mg, K, Fe, Cu, and Ga were found in the fly ash vapors at 1500°C.

In another study (50), fly ash was heated for several hours and changes in composition of the surface were studied. Generally two layers were resolved, but major differences were found depending on whether the fly ash was heated (to 1100°C) in air or in a vacuum. In air, Ca, Ti, Mg, and Fe were surface enriched and O, Al, Na, and Si were surface depleted; in a vacuum, Si and K were enriched while Ca, Mg, Fe, Al, and Ti were depleted. The authors concluded that surface segregation trends are time-temperature-profile and gas-phase-environment dependent, and that the rates of surface segregation are too slow for equilibrium concentrations to be established in normal firing and cooling processes.

In contrast, however, Hulett et al. (45) concluded from surface and heating studies that fly ashes are in near-equilibrium and not "frozen" transients. They also concluded "... that the qualitative nature of fly ash is independent of coal source and firing conditions."

There are many studies which report bulk trace element concentrations in different size fractions of fly ash. Typical of the better ones is the study reported by Campbell et al. (51) for a western coal-fired steam plant. Table 27 reproduces some of their findings; it also serves to illustrate the relative accuracy of three different analytical methods [X-ray Fluorescence (XRF), Atomic Absorption (AA) and Instrumental Neutron Activation Analysis (INAA)]. Table 27a gives data for the major and minor species (in %), while 27b gives data for trace elements (in ppm). Silicon alone shows a concentration decrease in the smaller size particles (Gladney (52) also reports a silicon decrease); most other major and minor species show a slight (~50%) increase (e.g., Fe, Al, Ti) or a substantial (~100%) increase (e.g., Ca, Mg, Na). Most of the trace elements show a substantial to a dramatic (>500%) increase in the smallest size ranges (e.g., Pb, As, Se). A consensus of several studies reports the following elements to be substantially enriched in the smaller particles: Sb, As, Cd, Cr, Pb, Ni, Se, Th, Zn (53).

Natusch (31) was probably the first to propose the concept that volatile elements condense on the greater relative surface area of the small particles and are thereby enriched. He proposed a simple inverse proportionality between concentration and diameter. Flagen and Friedlander (54) proposed a more complex theory predicting an inverse proportionality between concentration and the square of the diameter. The data do not particularly favor one theory over the other. In fact, where the quality of data permit, the concentration versus size curves seem to have structure (i.e., are not linear nor monotonic) and indicate that either multiple or complex mechanisms are at work (51).

TABLE 27a. MAJOR AND MINOR ELEMENT CONCENTRATIONS (wt %) IN DIFFERENT SIZE FRACTIONS OF WESTERN FLY ASH

Particle size, μm	Al, %		Br, %		Ca, %		Fe, %		Mg, %	
	INAA	AA	INAA	XRF	INAA	XRF	INAA	XRF	INAA	AA
0.5	10.7	11.3	1.44	1.23	6.6	5.14	3.47	3.32	3.86	4.6
2	10.0	11.0	0.87	0.78	5.5	6.16	3.20	3.15	3.18	3.8
4	10.6		0.76	0.62	7.0	6.71	3.22	3.11	4.5	2.29
5	9.56	10.3	0.50	0.45	6.7	6.53	2.89	2.79	3.09	4.9
8.5	9.35	9.6	0.39	0.34	7.0	5.99	2.66	2.46	2.51	2.15
12.5	8.80	7.7	0.27	0.21	4.6	3.33	2.10	1.69	1.75	4.2
15.5	7.31	7.4	0.26	0.20	4.5	3.16	2.20	1.51	2.56	2.9
25	6.95	6.9	0.31	0.31	2.4	2.25	3.02	2.30	2.71	3.5
50		8.2	0.23		2.01	2.01	1.56	1.91	2.8	1.37
									0.82	0.61

Particle size, μm	Mn, %		K, %		Si, %		Na, %		S, %		Ti, %	
	INAA	XRF	INAA	XRF	INAA	XRF	INAA	AA	INAA	XRF	INAA	XRF
0.5	0.086	0.095	1.41	1.08	22.0	21.3	2.05	2.09	0.08	0.64	0.79	0.79
2	0.069	0.070	1.24	1.07	22.1	23.5	1.85	2.00	0.05	0.75	0.78	0.78
4	0.064	0.065	1.33	1.02	24.0		1.78		0.05	0.71	0.82	0.82
5	0.055	0.051	1.20	0.91	24.3	24.2	1.79	1.69	0.05	0.72	0.75	0.75
8.5	0.043	0.043	1.11	0.84	24.4	26.7	1.47	1.57	0.04	0.72	0.69	0.69
12.5	0.032	0.026	0.89	0.74	28.9	29.4	1.20	1.15	0.03	0.63	0.54	0.54
15.5	0.032	0.025	0.94	0.66	19.2	29.5	1.08	1.07	0.01	0.62	0.59	0.59
25	0.021	0.019	0.72	0.63	33.1	24.3	0.76	0.81		0.61	0.54	0.54
50		0.015	0.72	0.59	28.0	36.2		0.59				0.47

Note: Column headings refer to analytical method. INAA = Instrumental Neutron Activation Analysis. XRF = X-Ray Fluorescence. AA = Atomic Absorption.

Source: Reference 51.

TABLE 27b. TRACE ELEMENT CONCENTRATIONS (ppm) IN DIFFERENT SIZE FRACTIONS OF WESTERN FLY ASH

Particle size, μ m	Sb		As		Br		Ce		Ca		Cr		Co		Cu	
	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF
0.5	23.5		82	79	6.2		180	115	5.01		230		25.7		501	
2	22.9		80	70	4.8		170	115	4.60		220		22.4		396	
4	21.6		75	67	4.0		180	132	4.48		220		22.4		345	
5	13.6		50	46	3.2		145	115	3.60		140		19.0		275	
8.5	11.0		32	29	1.6		135	121	3.36		150		16.2		241	
12.5	4.2		12	10.5	.9		110	78	2.89		75		16.0		156	
15.5	3.4		12	10.1			100	86	2.57		90		10.0		131	
25	1.9		4.1	4.6			80	75	2.20		60		11.3		105	
50				4.2				43					7.6		67	

Particle size, μ m	Ga		La		Pb		Mo		Ni		Rb		Th	
	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF
0.5	96		70.3	53	254		74		190	204	62.1		59	
2	77		73.7	74	172		44		130	111	56.1		56	
4	70		76.7	81	139		50		105	81	54.6		55	
5	52		72.8	64	96		40		67	63	51.8		48	
8.5	33		69.6	64	74		35		80	70	46.2		46	
12.5	14		53.4	30	44		33		36	29	43.1		40	
15.5			55.7	45	41		30		63	59	34.8		36	
25	5.4		41.9	36	22		27		35	22	34.7		32	
50	4.7			29	17		16		15				31	

Particle size, μ m	Se		Sr		Sn		V		Y		Zn	
	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF	INAA	XRF
0.5	68		59	1600	1910		51		48		190	
2	44		33	2080	2010		38		54		170	
4	30		26	2360	2100		28		61		140	
5	23		17.3	1720	2040		10		55		80	
8.5	12		11.6	1650	1840		9		49		70	
12.5	10		5.6	1270	1180		37		110		40	
15.5	7.9			1520	1140		8		88		35	
25	5.0		2.9	800	870				32		30	
50			3.9		610				28		10	

Note: Column headings refer to analytical method. INAA = Instrumental Neutron Activation Analysis. XRF = X-Ray Fluorescence. AA = Atomic Absorption.

Source: Reference 51.

3.3 SYNFUELS

3.3.1 Introduction

There are two major types of processes which convert coal to synthetic fuels: gasification and liquefaction. Coal gasification generally involves the reaction of coal with steam and air or oxygen. The gaseous fuel produced when air is used has a heating value of roughly 150 Btu/SCF and is known as low-Btu gas. When oxygen is used the gas has a higher heating value due primarily to the absence of nitrogen; a medium-Btu gas, with a heating value of 250 to 500 Btu/SCF, is the typical product. Medium-Btu gas may be used after suitable cleanup as a fuel or it may be upgraded via a number of catalytic processes to synthetic natural gas, synthetic liquid fuels (indirect liquefaction), or it may be used as a feedstock for the production of a number of chemicals, such as ammonia.

Coal liquefaction produces synthetic fuels either by the indirect route mentioned previously or directly by reacting the coal with hydrogen. The nature of the fuel produced by coal liquefaction depends on process conditions. It may vary from a low-melting point solid to a heavy fuel oil to a liquid feedstock refinable into gasoline and other distillate fuels.

Currently in the U.S., commercial-scale coal-conversion plants produce only low-Btu gas. Coal gasification facilities using a wide variety of technologies are in operation in other parts of the world. Several of these plants are based on the German-developed Lurgi technology. These include facilities at Westfield, Scotland; Kosovo, Yugoslavia, and the well-known SASOL indirect-liquefaction complexes in South Africa. A number of coal-conversion processes have been developed in the U.S. Among these are a number of gasification processes, including the Texaco entrained-bed gasification process and several direct-liquefaction processes, such as SRC I and II.

3.3.2 Synfuels Processes

Coal conversion processes have been designed which operate over fairly wide ranges of temperatures and pressures. The combination of operating temperature and pressure depends on the specific process. Direct liquefaction typically takes place at temperatures between 700-900°F and pressures from 500 to 4000 psi. Coal gasification is usually conducted at temperatures from 1200 to over 3000°F and at pressures from atmospheric to 1200 psi. Gasifiers may be divided into four main reactor types: underground (or in-situ), fixed-bed, fluidized-bed, and entrained-bed. Up to now, underground coal gasification in this country has been confined to a few experimental runs. In general, fixed-bed gasifiers operate at lower temperatures than fluidized-bed gasifiers, which in turn operate at lower temperatures than entrained-bed gasifiers.

Coal gasification and liquefaction are carried out under much different oxidant, temperature, and pressure conditions than coal combustion. Combustion occurs under oxidizing conditions, with excess air being used to assure that this is the case. Coal gasification and liquefaction, on the other hand, are carried out primarily under reducing conditions. Instead of sulfur oxides as produced during combustion, the major sulfur-containing gases produced under reducing conditions are hydrogen sulfide, carbonyl sulfide, carbon disulfide, and other organic sulfur species such as low-molecular weight mercaptans. The fraction of the coal sulfur converted to gaseous species appears to follow fairly closely the fractional conversion of the coal as a whole (55). Since gasifiers typically achieve nearly complete coal conversion, most of the sulfur will show up in the gas phase. Higher operating temperatures should result in greater loss of trace elements from the coal ash matrix and in increased production of lighter molecular weight sulfur species.

The scope of the present investigation has been limited primarily to an examination of the fates of sulfur and trace elements based on data obtained at commercial-scale or relatively large pilot-scale coal gasification facilities. The available data sources do not have, as their primary thrust, the

examination of sulfur and trace element fates. However, many present mass balance data for coal elements, including carbon, hydrogen, nitrogen, and sulfur, as well as for some trace elements.

No attempt has been made, within any of the available references, to correlate the fates of sulfur or trace elements with coal properties. Most of the studies present results of tests performed on a single coal.

The following general statements can be made relative to sulfur and trace element fates:

1. While the specific gasifier and/or coal combination may have some effect, sulfur appears predominantly in the product gas or in gasification by-products (such as tars and oils).
2. The predominant sulfur-containing gas species for all types of gasifiers and for all of the coals investigated is hydrogen sulfide; other species include carbonyl sulfide, carbon disulfide, and mercaptans.
3. Some trace elements exhibit higher volatility than others. There is a general, although not clear-cut, correlation between trace element boiling point and the fraction remaining in the ash.

3.3.3 Major Pollutant Streams

In general, gasification processes produce multiple output streams: ash (or slag), captured fines, by-product tars and oils, and crude product gas. In addition, if the product gas is cooled, an aqueous wastestream is generated. The unconverted solids are removed from the bottom of the gasifier and/or separated from the crude product gas stream using devices such as cyclones or scrubbers. Generally, the ash or slag stream is the largest waste stream.

Gasifiers operating at relatively low temperatures may produce significant quantities of tar and/or oil by-products. Because of their heating value, these by-products may be utilized either on or off site as boiler fuel, or they may be recycled to the gasifier for conversion to gaseous products. The tars and oils do not represent a wastestream, although their combustion will produce flue gas which may require cleanup.

The other major stream leaving the gasifier is the crude product gas. Depending on its end use, this gas may undergo several cleanup steps for the removal of residual entrained particles, aerosols, and/or pollutant gas species. Cooling the product gas results in the production of process condensate which may require cleanup prior to reuse and/or disposal.

The relative sizes of the gasifier outlet streams depend on a number of factors including:

- gasifier type,
- reactant gas composition, and
- coal ash and moisture content.

For example, tars and oils are not produced by high-temperature gasifiers such as entrained-bed types (e.g., Texaco, Koppers-Totzek). Also, low-Btu gasifiers using air produce a gas stream containing significant concentrations of diluent nitrogen; the product gas-to-coal ratio for these gasifiers is therefore higher than for oxygen-blown gasifiers. Gasifiers requiring large quantities of steam for temperature moderation (such as fixed-bed gasifiers) will produce more condensate than higher temperature designs. Coals with high moisture content also produce more process condensate. Similarly, coals having high ash contents produce more gasifier ash or slag than low-ash coals.

Data on the relative flow rates of product gas, ash, by-product tar and oil, and excess process condensate taken from the sources used in this investigation are summarized in Table 28.

3.3.4 Partitioning of Sulfur and Trace Elements

A survey of published synfuel characterization studies shows that, in most cases, most of the sulfur originally in the coal is found in the product gas and tar/oil by-products. Of the sulfur found in the gas phase, roughly 90 percent is usually in the form of hydrogen sulfide, with the remainder consisting of organic sulfur species, such as carbonyl sulfide, methyl mercaptan, carbon disulfide, and ethyl mercaptan. A compilation of published data on the fate of sulfur from a number of different gasifiers utilizing different feedstocks is given in Tables 29 and 30. One of the data sources indicates that the fraction of the coal sulfur remaining in the gasifier ash or slag depends on the coal, but no details are given. The data are also too limited to allow any correlation to be made. Malte and Rees (66) indicate that thermodynamic equilibrium would result in 96% H_2S and 4% COS for a general gasifier. The Texaco gasifier data in Table 30 appear to be in very good agreement with this equilibrium prediction.

The fates of a number of trace elements which are currently regulated or which are being considered for regulation as NESHAP pollutants, as well as others of potential environmental concern, are summarized in Tables 31 through 35. As can be seen from the tables, the major fraction of most trace elements usually remains in the gasifier ash/slag or other solids removed from the product gas. General exceptions are the volatile elements: fluorine, mercury, selenium, zinc and lead. However, closure on trace element mass balances are generally poor due to problems inherent in analyzing for species present in low concentrations and in the collection efficiency of the sampling methods, especially for gas phase trace elements.

TABLE 28. MASS FLOW RATES OF GASIFIER OUTLET STREAMS RELATIVE TO ASH PRODUCTION

Gasifier	Coal	Tar/Oil	Product Gas	Process Condensate	Reference
Lurgi	Rosebud	0.4	12.9	10.0	56
Lurgi	Illinois #6	0.4	18.2	22.7	56
Lurgi	Illinois #5	0.6	20.7	21.3	56
Lurgi	Pittsburgh #8	0.6	24.0	31.1	56
Lurgi	Kosovo lignite	0.3	5.0	4.9	57
Texaco	Illinois #6	0	14.6	4.3	58
Wellman-Galusha	N. Dakota lignite	0.4	23.6	NA	60
Wellman-Galusha	Anthracite	---	64.9	NA	61
Foster-Wheeler (Stoic)	Pinnacle Seam, Co.	0.1	26.6	2.4	62
Chapman	Virginia bituminous	1.5	49.5	NA	63
Riley	N. Dakota lignite	0.3	29.1	27.8	64

--- Not reported
NA - Not applicable

TABLE 29. SULFUR PARTITIONING IN COAL GASIFICATION

Gasifier	Coal	% of Output Sulfur in Stream				Reference
		Ash/Slag	By-Products	Gas		
Lurgi	Rosebud Seam, Montana	4.3	1.7	94.1	56	
Lurgi	Illinois #6	1.4	2.2	96.4	56	
Lurgi	Illinois #5	0.7	3.9	95.4	56	
Lurgi	Pittsburgh #8	1.0	3.0	96.0	56	
Lurgi	Illinois #6-rom	1.6	1.8	96.6	56	
Lurgi	Illinois #5-rom	—	1.4	98.6	56	
Lurgi	Pittsburgh #8-rom	—	2.3	97.7	56	
Lurgi	Rosebud-fine	9.5	3.2	87.3	56	
Lurgi	Kosovo lignite	1.3	2.6	96.0	57	
Toxaco	Illinois #6	2.0	—	98.0	58	
Koppers-Totzek	Not Specified	5-30 ^a	—	70-95	63	
Wellman-Galusha	N. Dakota lignite	16.8 ^b	3.2	79.7	60	
Wellman-Galusha	Anthracite	4.7 ^c	—	95.3 ^d	61	
Foster-Wheeler (Stoic)	Pinnacle Seam, Colorado	8.3	—	91.7	62	
Chapman	Virginia bituminous	43.1	17.1	39.8	63	
Riley	N. Dakota lignite	20.0 ^e	1.1	78.9 ^e	64	

^aRange only given—"depending on coal"^bIncludes S in cyclone dust^cIncludes coal hopper, potchole gas^dIncludes S in ash pan water

TABLE 30. GAS-PHASE SULFUR SPECIES

Gasifier/Coal	% of Gas-Phase Sulfur, As S					
	H ₂ S	COS	CH ₃ SH	C ₂ H ₅ SH	(CH ₃) ₂ S	SO ₂
Lurgi/Rosebud	94.0 ^a					
Lurgi/Illinois 6	98.4 ^a					
Lurgi/Illinois 5	97.8 ^a					
Lurgi/Pittsburgh 8	98.4 ^a					
Lurgi/Illinois 6-rom	98.3 ^a					
Lurgi/Illinois 5-rom	98.3 ^a					
Lurgi/Pittsburgh 8-rom	98.4 ^a					
Lurgi/Rosebud-fine	98.2 ^a					
Lurgi/Kosovo lignite	87.1	1.4	8.6	2.9		
Toraco/Illinois 6	96.8	3.2				
Koppers-Totzek/S. African bitum.	88.4	5.9			5.6	0.1
Wellman-Galusha/N. D. lignite	100.0 ^a					
Wellman-Galusha/anthracite	85.4	12.0			0.2	0.9
Chapman/Virginia bitum.	86.2	9.4			2.4	2.0
Riley/N. D. lignite	90.2	9.8				
Woster-Wheeler (Stoto)/Pinnacle Seam	87.8	9.0	2.6	<0.2		0.2

^aRemainder listed as "organic sulfur"^bNo other species analyzed

TABLE 31. TRACE ELEMENT PARTITIONING—LURGI GASIFIER, KOSOVO COAL

Element	% of Inlet Flow Accounted For	% of Outlet Flow in Stream		
		Ash	By-Products	Gas*
As	22.4	95.2	4.3	0.4
Be	42.9	99.1	0.9	0.01
Cd	303.2	97.9	2.1	0.02
Co	85.6	99.6	0.4	0.01
Cr	35.4	98.9	1.0	0.06
Cu	17.0	93.8	6.1	0.1
Hg	22.9	29.7	4.8	65.5
Mo	24.1	99.5	0.5	0.01
Ni	36.1	99.2	0.8	0.02
Pb	115.1	93.6	6.3	0.09
Se	14.2	95.0	3.6	1.4
V	123.0	99.8	0.2	0.01
Zn	1.6	18.7	68.6	12.7

*Includes trace elements in gas liquor

Source: Reference 57

TABLE 32. TRACE ELEMENT PARTITIONING TEXACO GASIFIER, ILLINOIS #6 COAL*

Element	% of Inlet Flow Accounted For	% of Outlet Flow in Stream	
		Slag/Solids	Gas**
As	45.8	99.7	0.3
Be	154.3	98.9	1.1
Cd	72.7	99.8	0.2
Co	297.6	99.9	0.1
Cr	362.7	99.99	0.01
Cu	76.0	99.95	0.05
Mn	95.8	99.9	0.1
Mo	154.0	100	—
Ni	68.8	99.9	0.1
Pb	39.2	98.8	1.2
Sb	28.2	99.8	0.2
Se	77.7	94.9	5.1
V	161.3	100	—
Zn	61.8	99.6	0.4

*Represents average of 6 tests

**Includes trace elements in excess water

Source: Reference 58

TABLE 33. TRACE ELEMENT PARTITIONING FOSTER--WHEELER
(STOIC) GASIFIER, PINNACLE COAL

Element	% of Inlet Flow Accounted For	% of Outlet Flow in Stream		
		Ash/Dust	Oils	Gas*
As	178.6	97.9	0.4	1.7
B	356.4	99.1	0.02	0.9
Be	38.7	99.5	—	0.5
Cd	67.1	99.7	—	0.3
Co	98.7	99.2	0.6	0.2
Cr	161.6	66.5	30.1	3.5
Cu	106.5	79.7	0.05	20.2
F	226.1	95.4	0.4	4.2
Hg	70.4	75.9	4.8	19.3
Mn	231.2	99.9	0.01	0.1
Mo	73.2	98.4	0.4	1.3
Ni	—	—	—	—
Pb	92.9	78.5	0.2	21.3
Sb	41.8	47.8	3.6	48.6
Se	24.9	88.8	4.8	6.5
V	88.8	99.8	—	0.2
Zn	58.1	80.0	0.3	19.6

*Includes trace elements in outlet water

Source: Reference 62

TABLE 34. TRACE ELEMENT PARTITIONING WELLMAN-GALUSHA GASIFIER, N. DAKOTA LIGNITE

Element	% of Input Flow Accounted For ^a		% of Output Flow in Stream			
	Ash	Ash Slurries Water	Gas Particulates	Gas Organics Module		
As	74.3	0.01	24.5	1.2		
B	92.8	0.7	6.4	0.2		
Be	99.2	—	0.8	—		
Cd	10.0	0.1	90.0	—		
Co	98.2	0.1	1.7	0.1		
Cr	97.3	0.1	2.3	0.4		
Cu	91.4	0.1	8.2	0.3		
F	83.6	0.1	16.1	0.1		
Hg	0.1	0.1	99.0	0.1		
Mn	98.4	0.1	1.5	0.1		
Mo	97.5	0.7	1.8			
Ni	95.7	0.1	3.9	0.3		
Pb	53.6	0.1	38.1	8.3		
Se	3.6	0.1	92.5	0.1		
Se	3.4	0.1	96.6	0.1		
V	99.7	0.1	0.2	0.1		
Zn	58.9	0.1	38.5	2.5		

^aData not presented

Source: Reference 60

TABLE 35. TRACE ELEMENT PARTITIONING RILEY GASIFIER, N. DAKOTA LIGNITE

Element	% of Input Flow Accounted For	% of Outlet Flow in Stream			
		Ash/Dust	Ash Pan Water	Gas Aerosols	Gas Vapor
As	34.2	68.6	0.8	24.6	6.0
B	62.9	53.8	36.2	1.6	8.3
Ba	32.4	13.0	—	1.5	85.5
Cd	3.2	25.6	—	18.8	56.3
Co	83.4	>93.8	<0.9	<1.8	<3.6
Cr	33.3	<16.9	<0.2	73.9	9.0
Cu	68.6	93.2	0.4	6.3	0.3
F	35.5	52.4	8.3	5.0	34.2
Hg	20.4	2.7	4.0	—	94.5
Mn	215.6	98.1	0.7	1.1	0.2
Mo	62.3	75.3	18.0	5.6	1.1
Ni	54.4	88.9	0.4	5.6	5.1
Pb	159.1	36.4	0.1	43.6	19.9
Sb	49.5	26.0	3.8	56.6	13.7
Se	99.1	23.0	4.3	3.7	69.0
V	71.6	98.5	0.1	1.1	0.3
Zn	85.2	66.7	0.2	30.3	2.8

Source: Reference 64

The available data on sulfur and trace element partitioning especially in coal gasification systems have not generally been correlated with coal properties. However, as would be expected, coals having higher concentrations of sulfur and various trace elements tend to produce higher concentrations of these species in the process streams. The report on Koppers-Totzek gasification indicates that the fraction of coal sulfur remaining in the ash depends on the coal, but no details are given as to the form this dependency might take.

3.3.5 Summary and Conclusions

3.3.5.1 Environmental Significance of Sulfur and Trace Elements in Effluents

Since the bulk of the sulfur entering a given coal gasifier will leave in the crude product gas, to reduce subsequent SO_2 emissions it will usually be necessary to either remove the reduced sulfur species prior to combustion or remove sulfur oxides from the flue gas after combustion. Given the relative ease of removing hydrogen sulfide compared to sulfur dioxide and the relative flow rates of the streams to be treated before and after combustion, the former route would appear to make the most sense. The presence of sulfur species in addition to hydrogen sulfide, as well as other constituents of the raw gas (such as hydrocarbons), must be taken into consideration in selecting and operating a removal process.

The sulfur content of the liquid by-products of some gasification processes may limit the uncontrolled combustion of these materials. Sulfur dioxide scrubbing may be required to meet environmental regulations.

Trace elements will, for the most part, be found in gasification plant solid wastes, including gasifier ash or slag and captured fines. The environmental impact of these materials will depend on their leaching characteristics upon disposal. Results of RCRA Extraction Procedure leaching tests of gasifier ashes/slugs have usually shown these materials to be non-hazardous.

Fused slags produced by high temperature gasifiers can be expected to present a lower potential for trace element environmental availability due to leaching.

Volatile trace elements which are present in raw product gas may be removed to some extent as the gas is cooled and scrubbed. Their environmental impact would then be transferred to aqueous streams which will likely require treatment prior to reuse or disposal. Evaporative treatment processes might concentrate trace elements to levels which would pose environmental problems. Volatile trace elements not removed by scrubbing may eventually appear in the final product gas and pose an environmental problem after combustion of the gas. No data are available to predict these impacts.

3.3.5.2 Existing Knowledge on the Effect of Coal Properties on Sulfur and Trace Element Partitioning

Other than the reference to the dependence on coal of sulfur partitioning mentioned for the Koppers-Totzek gasifier (11), no data were found correlating coal properties to sulfur or trace element partitioning. The reports containing sulfur and trace element balances most often present data obtained from coals which were not characterized with respect to trace element mineral forms.

Since the majority of the sulfur in a given coal is usually converted to gaseous species, coals with higher sulfur concentrations will necessarily result in higher sulfur emissions.

Coal property effects on trace element partitioning are difficult to correlate given the difficulty of obtaining accurate mass balances for species which are present in such low concentrations. In addition, the studies reviewed do not present any information on the mineral forms in which the trace elements are present in the original coal. Intuitively it seems likely that a

combination of reactor temperature, residence time, reactor atmosphere, and coal mineral composition may be the important factors influencing trace element partitioning.

3.4 LEACHING OF COAL WASTES

3.4.1 Introduction

Coal utilization by the electric power industry generates more than 70 million tons of solid waste per year. These wastes include refuse from coal preparation plants, bottom ash and fly ash from coal combustion, and flue gas desulfurization wastes. Most of these utility wastes are nonhazardous and are disposed in landfills. However, because of their large volumes, constituents released from coal-fired utility wastes through leaching may constitute a potential hazard. Field and laboratory studies have been used to predict leachate migration; data generated by these studies may subsequently be used as input into computer models to identify correlations and to predict leachate behavior.

The Environmental Protection Agency has defined leachate as "liquid that has passed through or emerged from solid waste and contains soluble, suspended, or miscible materials removed from such wastes" (67). Leachate can originate from water used in waste transport, interstitial water, precipitation, surface inflow, or ground-water inflow which has percolated through a waste body. The resultant outflow from a landfill or pond may contain soluble or colloidal species which have been removed from the waste.

Leachate from coal waste disposal areas, whether pond or landfill, has been a matter of concern due to its potential for entering either surface or groundwater. Leached species may be deleterious to ground and surface waters which are ingested by humans, animals, and aquatic life.

Leachate pathways into ground water are often indirect, difficult to observe, and difficult to trace. Because ground water moves slowly, pollution from leachate may not be detected for many years, and once leachate leakage is detected and corrected, the existing contamination problems may persist for long periods. Regulatory agencies, therefore, have set forth guidelines pertaining to the contamination of ground waters from leachate. Levels of trace metal concentrations in waste leachate have received specific attention. The main question is: "What are the chemical characteristics of the leachate and will this leachate be detrimental to water usage?"

A substantial amount of work has been performed on the leaching of coal wastes. Leaching behavior of coal preparation wastes, ashes, and flue gas desulfurization (FGD) sludges has been studied to determine potential environmental impacts of land disposal and to evaluate different leaching procedures. The relationship of coal properties to the leachate from coal wastes, a principal point of this study, is not directly addressed in the open literature. Although general ranges of coal ash leachate quality can be approximated from information on what was originally in the coal, specific or quantitative correlations between coal properties and coal ash leachate are not available. While some studies of ash contain information on the coal, the majority of leachate data are limited to correlation of the bulk composition of solid wastes with leachate quality. These correlations are usually found only for specific experimental parameters, such as solid-liquid ratio, extraction method, pH, temperature, and atmospheric conditions.

The most useful correlation of coal properties to leachate properties may be accomplished for coal preparation wastes which are not affected by the combustion process. Table 36 summarizes the major factors affecting leaching. Leaching is affected by waste type, waste composition, the liquid phase composition in contact with the waste, and the manner in which the solids and liquids are contacted. Each of these factors is affected by other parametric conditions as listed in Table 36.

TABLE 36. SUMMARY OF FACTORS AFFECTING LEACHING

Category	Factor		Definition	Comments	References
	Parameter				
Waste Type	Coal Preparation (Cleaning) Wastes		Mineral matter washed from coal prior to firing.	Major constituents are iron, sulfur, aluminum, potassium, calcium, magnesium, titanium, and sodium.	70-72
	Fly Ash (Boiler)		Ash produced from coal combustion composed primarily of silicates ranging in particle size from 1 to 100 μm .	Major constituents are silicon, aluminum, magnesium, calcium, potassium, titanium, and iron.	73-79
	Bottom Ash (Boiler)		Vitrified, inert residue from direct combustion of coal ranging in particle sizes >100 μm .	The physical characteristics of bottom ash are dependent on the quenching and crushing process at the base of the boiler. This ash is generally rather inert.	75, 76, 78, 79
	Gasifier Ash		Residue from gasification of coal. This ash is similar in composition to fly ash.	Different gasification processes (Lurgi, Cogas, Texaco) will cause waste properties to vary. It is usually more inert than fly ash.	80-83, 93
	Fluidized Bed Combustion Waste		FBC wastes consist of spent limestone or dolomite, CaSO_4 , CaO , CaCO_3 , MgO , and coal ash.	Low-temperature processing provides better quality leachate.	84, 85
Waste Composition	FGD Sludge (sometimes containing large amounts of fly ash)		The major constituents of the sludge are $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and CaSO_3 , $\text{CaSO}_4 \cdot \frac{1}{2} \text{H}_2\text{O}$ with small amounts of fly ash and sorbed trace metals.	Initial leaching of sludge results in high release rates which level off to a dissolved solids concentration controlled by the solubility of CaSO_3 and CaSO_4 .	75, 77-79, 86
	Age		The chemical composition of the waste is greatly dependent on the age of the waste and the conditions the waste was stored under during the aging or curing process.	This parameter is especially critical for pyritic wastes which become highly acidic under air oxidation.	70-72, 74, 76, 78, 84, 85, 87
	Mineralogy		The mineral form in which a trace element occurs or is partitioned into during condensation following combustion will often determine the phase's solubility and subsequent release of a given chemical species.	SEM and x-ray diffraction has been used to identify mineral morphology.	72-75, 77, 78, 80-82, 84-88, 90-97, 100-103
Particle Size			The particle size distribution will control surface related solubility controls, i.e., the larger the surface area, and the smaller the particle size, the higher the reactivity.	Particle size also affects pore size and permeability, solubility, adsorption, and mass transfer.	71-75, 77-87, 98
	Porosity		The amount of intra- and interstitial spaces available for contact of waste with leaching fluid can determine the equilibrium composition of the waste solution.	Porosity can be manually stipulated in disposal by waste compaction.	75, 77-79, 83, 85, 87

(Continued)

TABLE 36. (Continued)

Factor		Definition	Comments	References
Category	Parameter			
Waste Composition (Continued)	Combustion Process	The processing of the coal will determine which species are oxidized, whether or not glasses will be produced, the amount of incomplete combustion products, the carbon content, enrichment of trace elements, removal of sulfur, and final condensation of the solids.	Temperature of combustion and type of combustion process have been notably effective in controlling environmental stability of FBC wastes.	71, 72, 77-79, 81-85, 87
	Waste Treatment	Studies have shown that rate of leaching and solute concentrations can be reduced by chemically stabilizing, fixing, or solidifying wastes.	Fixation processes seem to be more successful with alkaline ashes.	71, 72, 75, 76, 78, 79, 83, 84
	Waste Homogeneity	Leaching may vary for inhomogeneous wastes produced by different feedstock, process conditions, and waste treatment.	For disposal of wastes which will involve comingling of waste streams, leaching experiments have shown both enhancement and retardation of leaching of comingled wastes.	74, 75, 78, 79, 81, 83, 85-87, 105
	Armoring	Armoring is the process that occurs usually during cyclic wetting/drying that yields a solid phase surface for leaching uncharacteristic of the composition of the bulk solid.	Armoring can be detected by ESCA (for thin layers) and ion probe analysis (for thicker layers).	74, 85, 87, 88, 90-92, 99-94, 99-104, 106, 107, 110-117
Liquid Phase Composition	pH	pH is defined as the negative log of the hydrogen ion concentration.	The pH of rainwater is controlled primarily by dissolved CO ₂ .	70-75, 77, 81, 82, 84, 87
	Eh	Eh is the redox potential of a system as defined by the Nernst Equation.	Eh determines in part the aerobic or anaerobic conditions under which a material is leached.	71, 72, 74, 77, 82, 83, 87
Buffer Capacity	Buffer Capacity	The buffer capacity defines the resistance of a system to changes in pH upon the addition of acids or bases.	Naturally occurring leachate exists as a highly buffered system.	76, 81, 83, 87
	Complexation Capacity	Complexation is defined as the formation of a complex from a metal ion with a neutral or negative ion by means of one or more chemical bonds.	The most effective complexing agents are generally organic compounds.	87
	Ionic Strength	The ionic strength of a solution, I , is defined as $I = \frac{1}{2} \sum C_i Z_i^2$, where C_i is the concentration of an ion in moles per liter; Z_i is its charge, and the sum is taken over all ions in solution.	In general, the solubility of an ionic salt is roughly proportional to the square root of I for dilute solvents.	85

(Continued)

TABLE 36. (Continued)

Factor		Definition	Comments	References
Category	Parameter			
Liquid Phase Composition (Continued)	Temperature	Temperature is an intensive property of a system and defines the direction of heat flow between systems.	Temperature within a disposal site may vary significantly with seasonal temperature changes; natural systems are not likely to be in complete equilibrium due to local energy fluxes within a landfill.	80,82,84,90
	Oxic/Anoxic	The presence or absence of oxygen during leaching can be responsible for oxidizing or reducing conditions.	After landfills are covered, anoxic conditions usually develop, changing the system to anaerobic favored reactions.	75,78,79,83,87
	Surface Area/Permeability	The surface area is usually defined experimentally by the measurement of some property that qualitatively depends on the extent of surface and can be related to absolute surface area.	Particle size of landfilled materials usually decreases with time due to physical and chemical weathering processes.	71,72,74,75,77-81,83-85,87,93
Solid-Liquid Contact	Solid-Liquid Ratio	Weight ratios are commonly used to define the ratio.	In field studies the liquid-to-solid ratio is difficult to define and varies with time.	75-79,81-83,85,87
	Contract Duration	Contract duration refers to the amount of time (residence time) elapsed between an eluant and the solid leached.	While some chemical reactions will occur rapidly (e.g., cation exchange), others will proceed slowly (redox).	71,72,74,75,78,79,81-83,85-87
	Saturation Cycles	In actual leaching, the solids may undergo many physical and chemical changes as a result of wetting/drying periods in the natural environments.	Saturation cycles will vary with disposal sites, i.e., the Western U.S. may undergo fewer than the Eastern U.S.	71,72,75,78,79,83,85,87,108,109
Extraction Technique	Temperature Cycles	Extreme changes or rapid changes in temperature are more likely to cause alterations in the leaching of solids.	Freezing of leaching fluid in interstitial sites may result in cracking and subsequent channeling and piping of the leaching fluid through the waste body.	84
	Extraction Technique	Four general methods of extraction (leaching) are considered in this study: (1) batch leaching, (2) sequential batch leaching, (3) column leaching, and (4) test cells or lysimeters.	Batch leaching is most useful at defining the availability of species for extraction. Sequential batch leaching supplies species availability for extraction plus extraction efficiencies at incremental time periods. Column leaching allows information of extraction efficiency under dynamic flow and gives continuous extraction rates. Test cells also define dynamic flow but add actual field conditions.	70-87,89
	Agitation	Static agitation refers to interaction in the absence of agitation after initial mixing. Dynamic agitation refers to constant shaking or increased, artificially accelerated mixing.	Method of agitation controls solution species concentrations by causing particle shearing and increased collisions.	70,75,77,78,80,81,85

3.4.2 Leaching Methods

Leachates from coal wastes can be partially described by their elemental concentration of major constituents and trace elements. Leachate characteristics are determined by various leaching methods, the four principal ones being: RCRA EP, ASTM, column, and field leaching as described below and summarized in Table 37. This section briefly describes each of these methods and discusses the general characteristics of leachates from coal preparation and combustion wastes.

RCRA EP leachate is the extract generated by the EPA Resource Conservation and Recovery Act (RCRA) Extraction Procedure (EP) which is given in detail in the May 19, 1980 Federal Register (68). Basically this procedure involves the addition of acetic acid to maintain a pH of 5 in an aqueous 24-hour batch leaching. The volume-to-mass ratio is set at 20:1.

ASTM leachate refers to the extract produced by the proposed Method A extraction procedure as described in American Society for Testing and Materials "Proposed Method for Leaching Waste Material" (69). In the ASTM extraction, a four to one volume-to-mass ratio of liquid (deionized water) to solids (waste) is batch leached for 48 hours. No pH adjustment is made during the test period.

Column leaching is performed in a variety of ways. There is no standard method for this procedure. However, a method for inorganic wastes is currently under consideration and is designated as ASTM D34, Solid Waste. Generally, it involves packing waste(s) into an inert glass, plastic, or stainless steel column, and eluting a liquid through the packed material while monitoring resultant leachate (eluant) parameters. The duration of the column test varies depending upon the test objectives.

TABLE 37. SUMMARY OF EXTRACTION/LEACHING TECHNIQUES

Extraction Technique	Information Obtained	Advantages/Disadvantages
<u>Laboratory Tests</u>		
Batch	Leaching potential. ECHA EP at controlled acidic pH. ASTM at floating pH.	Simple, inexpensive, reproducible/not dynamic, flow conditions not considered, unnatural solid-liquid contact, difficult to interpret.
Sequential Batch	Leaching potential plus extraction efficiency at incremental time periods.	Inexpensive, quick, simulates leaching sequence/Flow not considered, unnatural solid-liquid contact, requires more sophisticated predictive models but easier to interpret than batch, can control all important variables adequately and allow evaluation of effect of one parameter.
Column	Leaching potential under dynamic flow. Continuous extraction rate.	Dynamic flow, natural solid-liquid contact, simulates leaching sequence, requires a less sophisticated predictive model, analytical data easier to interpret, better simulates field condition/Expensive, time consuming, does not allow for effects of local climatic conditions.
<u>Field Tests</u>		
Test Cells	Leaching potential under dynamic flow. Leaching and climatic conditions of the field.	Larger sample size, better simulates field conditions with respect to climatic conditions, easiest to interpret/Less control, more expensive, longer time duration, no leachate-ground water interaction.
Disposal Site Collection	Extraction from existing dumped waste which has produced leachate under site-specific conditions.	Actual leachate collection usually can not occur for years after disposal and therefore require longer time and more climatic changes to be considered. These data are generally hard to interpret with the quantity of parametric control variations with time.

Field leachates are liquids collected from wastes that are undergoing the leaching process under climatic conditions in an actual field situations. These leachates represent landfill and pond effluents as well as sluicing water.

3.4.3 Partitioning of Sulfur and Trace Elements

The wastes associated with coal use have been segregated in this report as pre-combustion and post-combustion wastes. Waste material generated by pre-combustion refers to waste from coal cleaning processes. Post-combustion wastes include bottom ash, fly ash, and FGD sludge.

3.4.3.1 Coal Cleaning Wastes

Coal cleaning (or preparation) wastes are produced when mineral matter is removed from coal prior to combustion, conversion to synthetic fuels or coke, or other final uses. One-half of the coal mined in the U.S. is cleaned. The resultant waste contains a variety of inorganic materials ranging from fine-grained clays to sands, shales, and macroscopic mineral nodules. For example, Table 38 shows the average weight percent content of major minerals present in

TABLE 38. MAJOR MINERALS IN REFUSE FROM ILLINOIS BASIN
COAL PREPARATION PLANTS A, B, AND C

Mineral	Plant A Average - Wt. %	Plant B Average - Wt. %	Plant C Average - Wt. %
Kaolinite	15	7	14
Illite	14	11	16
Other Clays	7	17	8
Pyrite	14	15	21
Marcasite	8	11	9
Quartz	22	17	23
Calcite	6	0	1
Gypsum	3	1	1
Other	11	21	7

Source: Reference 71

coal preparation wastes from three plants using Illinois Basin coal. Elements usually associated with individual minerals are shown in Table 13 in Section 2.3. Elements generally found in coal refuse at or above the one percent level include iron, sulfur, aluminum, silicon, potassium, calcium, magnesium, titanium, and sodium. Chromium, copper, manganese, nickel, and zinc may also be present in significant amounts. Many other trace elements can be found in the refuse in the same relative abundance as in crustal rock. Multiple analyses of the same refuse shows ranges for most elements of ± 25 percent of the mean. Differences between wastes from different locations are even greater (71).

Because the coal cleaning process (involving grinding) produces many newly exposed surface areas, cleaning wastes are highly susceptible to leaching. In addition and for similar reasons, the cleaned coal itself is more leachable when compared to untreated, unground feed coal (see Table 39). Smaller particles which have a greater relative surface area similarly show a higher initial degree of leaching. However, after longer periods of time, equilibrium conditions are approached, and differences in leachate concentrations from different size fractions (see Table 40) are reduced.

The RCRA EP has been used on coal cleaning wastes to determine potential toxicity classification under RCRA. Although most coal cleaning wastes would not be classified as hazardous using the RCRA EP toxicity test, leachates from coal cleaning wastes often contain high concentrations of various pollutants (F, Al, Mn, Fe, Co, Ni, Cu, and Zn). Column (dynamic) leaching studies, more representative of actual field behavior, show several elements not addressed in the RCRA EP criteria to be present in high enough concentration to be of concern (see Table 41).

A major concern, especially in the eastern U.S., is the acidic leaching of high sulfur coal wastes (pyrite). Due to bacterial action, the sulfur is converted to acids, and the acidic leachate tends to mobilize trace elements

TABLE 39. AVERAGE LEACHATE COMPOSITIONS FROM STATIC LEACHING EXPERIMENTS WITH
FEED COAL, CLEANED COAL, AND COAL PREPARATION WASTES FROM AN
APPALACHIAN COAL SOURCE

Feed Coal												
Time (Days)	pH	Cond (mho/cm)	Be (ppm)	Al (ppm)	Mn (ppm)	Fe (ppm)	Co (ppm)	Ni (ppm)	Cu (ppm)	Zn (ppm)	As (ppm)	Pb (ppm)
1	2.8	0.97	0.007	5.5	0.8	86	0.35	0.5	0.30	1.1	0.01	0.008
5	2.8	1.13	<0.005	7.4	1.1	135	0.37	0.6	0.43	1.5	0.03	0.009
25	2.4	3.35	0.007	18	6.2	930	0.61	0.8	0.15	2.5	0.3	0.03
50	2.2	3.20	0.012	16	2.6	580	0.68	1.0	1.07	3.1	0.4	0.02
												0.028
												0.05
Cleaned Coal												
Time (Days)	pH	Cond (mho/cm)	Be (ppm)	Al (ppm)	Mn (ppm)	Fe (ppm)	Co (ppm)	Ni (ppm)	Cu (ppm)	Zn (ppm)	As (ppm)	Pb (ppm)
1	2.5	2.60	0.012	35	3.9	650	0.80	1.0	0.74	3.3	0.6	0.04
5	2.4	2.40	0.013	35	4.4	770	0.73	1.0	0.74	3.4	0.3	0.008
25	2.3	3.95	0.023	45	4.5	1040	0.88	1.2	0.88	3.8	1.3	0.02
50	2.2	3.80	0.024	49	4.7	890	0.92	1.3	1.15	6.1	1.4	0.032
												0.01
Preparation Wastes												
Time (Days)	pH	Cond (mho/cm)	Be (ppm)	Al (ppm)	Mn (ppm)	Fe (ppm)	Co (ppm)	Ni (ppm)	Cu (ppm)	Zn (ppm)	As (ppm)	Pb (ppm)
1	3.0	1140	0.012	4.7	3.3	181	0.63	1.0	0.66	1.0	0.05	0.15
5	2.9	1520	0.023	9.9	3.1	295	0.84	1.3	0.82	2.0	0.06	0.017
25	2.0	5200	0.046	72	24	1940	1.22	1.8	3.74	5.7	3.0	0.041
50	1.6	14400	0.043	110	23	9250	1.56	2.8	2.60	6.5	18.0	0.039
												<0.01

Source: Reference 72

TABLE 40. STATIC BATCH LEACHING OF DIFFERENT SIZE FRACTIONS OF AN ILLINOIS BASIN COAL WASTE IN THE PRESENCE OF AIR

Elements Leached (% available in waste) from Size Fraction Less than 0.84 mm Diameter														
Leaching Time (days)	Fe	Al	Na	K	Mg	Ca	Cr	Mn	Co	Ni	Cu	Zn	Cd	Pb
1	9.0	1.9	1.3	0.07	12	90	1.0	21	70	46	3	41	50	3
7	9.0	1.8	1.0	0.05	11	84	0.4	22	65	46	3	53	58	2
28	26	2.1	0.20	0.00	11	89	1.1	27	68	50	21	76	76	2
56	46	2.2	0.10	0.01	12	90	1.2	32	70	54	36	100	82	3

Elements Leached (% available in waste) from Size Fraction Less than 9.35 mm Diameter														
Leaching Time (days)	Fe	Al	Na	K	Mg	Ca	Cr	Mn	Co	Ni	Cu	Zn	Cd	Pb
1	6	0.8	0.9	0.27	8.2	62	0.4	15	50	33	7	26	32	2
7	8	0.6	0.9	0.17	8.6	76	0.5	18	68	39	7	34	40	2
28	20	1.2	1.0	-	10.0	59	0.8	32	66	47	28	44	47	2
56	37	1.7	1.1	0.01	11.5	100	1.0	42	78	60	48	51	58	2

Source: Reference 71

TABLE 41. LEACHATE COMPOSITIONS FROM DYNAMIC (COLUMN) LEACHING OF
HIGH SULFUR APPALACHIAN COAL WASTE

Sample	Time (hrs)	Can Vol (m ³)	H ₂ O/ g Waste	pH	Cond (mho/cm)	Fe (ppm)	Ni (ppm)	Mn (ppm)	Zn (ppm)	Cd (ppm)	Al (ppm)	Cu (ppm)	As (ppm)	Co (ppm)	Pb (ppm)	Be (ppm)	Se (ppm)	Ag (ppm)	Ba (ppm)
33-1	17.2	105	0.205	2.14	6.80	2410	4.8	20.0	10.5	0.10	95	3.38	2.2	3.14	0.60	0.09	0.02	<0.01	<0.1
33-2	20.5	203	0.396	2.20	6.00	1920	4.1	17.2	10.0	0.07	79	2.64	1.6	2.81	0.43	0.08	0.01	<0.01	<0.1
33-3	23.8	301	0.588	2.27	5.20	1600	3.3	14.9	7.8	0.06	65	1.99	1.1	2.31	0.30	0.07	0.02	0.06	<0.1
33-4	39.5	576	1.12	2.51	3.60	980	2.0	10.4	6.3	0.03	36	0.94	0.66	1.19	0.17	0.03	<0.01	<0.01	<0.1
33-5	43.0	676	1.32	2.81	2.15	510	1.0	6.4	2.7	0.03	15.2	0.32	0.34	0.72	0.08	0.02	<0.01	<0.01	<0.1
33-6	46.8	786	1.54	2.89	1.82	420	0.8	5.4	8.0	0.02	11.3	0.23	0.30	0.40	0.06	0.01	<0.01	<0.01	<0.1
33-7	63.5	1001	1.96	3.04	1.32	300	0.59	4.2	2.6	0.01	6.2	0.13	0.23	0.41	0.04	0.01	<0.004	<0.01	<0.1
33-8	67.5	1114	2.18	3.19	1.02														
33-9	70.5	1221	2.38	3.29	0.840														
33-10	88.1	1761	3.49	3.45	0.310	55	0.10	1.12	0.30	0.01	0.4	0.03	0.09	0.08	0.01	<0.01	<0.004	<0.01	<0.1
33-11	91.8	1873	3.66	3.47	0.350	30	0.08	0.74	0.26	<0.01	0.2	0.02	0.03	0.03	0.01	<0.01	<0.004	<0.01	<0.1
33-12	-	1976	3.86	3.50	0.295														
33-13	117.0	2631	5.18	3.80	0.200	13	0.02	0.37	0.08	<0.01	<0.1	0.01	0.04	0.01	<0.01	<0.01	<0.004	<0.01	<0.1
33-14	160.7	3992	7.80	3.93	0.124	970	2.06	20.5	17.1	0.04	50.4	1.70	0.58	1.27	0.02	0.04	0.01	<0.01	<0.1
33-15	164.7	4111	8.03	4.03	0.100	690	1.50	14.7	6.1	0.02	35.5	1.10	0.34	0.92	0.03	0.03	0.02	<0.01	<0.1
33-16	319.5	4695	9.17	2.36	4.60	570	1.26	12.5	5.2	0.02	28.2	0.83	0.26	0.73	0.01	0.02	0.01	<0.01	<0.1
33-17	522.0	4770	9.32	2.44	3.65	440	0.95	9.7	3.9	0.02	19.9	0.57	0.19	0.56	0.01	0.02	0.01	<0.01	<0.1
33-18	523.0	4849	9.47	2.50	3.23	340	0.71	7.3	5.6	0.01	13.8	0.39	0.17	0.43	0.01	0.01	<0.01	<0.01	<0.1
33-19	525.5	4972	9.71	2.57	2.67														
33-20	527.5	5064	9.89	2.73	1.93														
33-21	543.5	5629	11.0	2.97	1.09														
33-22	545.5	5715	11.2	3.18	0.650	49	0.10	1.35	0.35	0.01	0.8	0.02	0.05	0.05	0.01	<0.01	<0.004	<0.01	<0.1
33-23	550.0	5833	11.4	3.23	0.550														
33-24	551.5	5960	11.6	3.29	0.450														
33-25	567.5	6550	12.8	3.43	0.345														
33-26	570.0	6634	13.0	3.54	0.217	19	0.02	0.60	0.12	<0.01	0.1	0.01	0.03	0.01	<0.01	<0.01	<0.004	<0.01	<0.1
33-27	573.0	6749	13.2	3.59	0.210	17	0.02	0.56	0.11	<0.01	0.1	<0.01	0.03	0.02	<0.01	<0.01	<0.004	<0.01	<0.1
33	575.5	6861	13.4	3.62	0.195														

Source: Reference 72

much more effectively. Intermittent column leaching studies done by Los Alamos Scientific Laboratory with high sulfur coal wastes have shown that discontinuous leaching, a condition likely to exist in the field, can result in significant pyritic oxidation and acid generation (72).

3.4.3.2 Boiler Bottom Ash

Boiler bottom ash is a vitrified, relatively inert residue. As shown in Table 42, it generally contains lower concentrations of the more volatile trace elements (As, Se, Cd, F, Mo, Pb, S, and Zn) than fly ashes. While solid-phase fly ash and bottom ash contain similar major constituents which generally control bulk solution chemistry, leachates from fly ash and bottom ash ponds in general are markedly different with respect to trace element concentrations (see Table 43).

Physical characteristics of bottom ash are dependent on the post-combustion quenching process and crushing. Selected physical characteristics of bottom ash are compared to fly ash and FGD sludge in Table 44. Generally, bottom ash is a denser, more permeable material than fly ash.

A survey of acidic (RCRA EP) leachate compositions for bottom ashes and neutral (ASTM) leachate compositions for bottom ash is shown as a function of coal regions in Tables 45 and 46. These compositions indicate that acid addition for the RCRA EP does not appear to appreciably affect the minimal leachability of the bottom ash.

3.4.3.3 Boiler Fly Ash

Boiler fly ash is generally removed from the flue gas by electrostatic precipitators or fabric filters. Major elemental composition of fly ash is similar to bottom ash, both consisting of primarily silicon, aluminum, magnesium, calcium, potassium, titanium, and iron. Certain of the low valence

TABLE 42. COMPARISON OF CONCENTRATION OF SPECIES IN FLY ASHES
AND BOTTOM ASHES FROM SIX UTILITY PLANTS

Compound or Element	Plant 1		Plant 2		Plant 3		Plant 4		Plant 5		Plant 6	
	FA	BA	FA	BA	FA	BA	FA	BA	FA	BA	FA	BA
SiO ₂ , %	59	58	57	59	43	50	54	59	NR	NR	42	49
Al ₂ O ₃ , %	27	25	20	18.5	21	17	28	24	NR	NR	17	19
Fe ₂ O ₃ , %	3.8	4.0	5.8	9.0	5.6	5.5	3.4	3.3	NR	NR	17.3	16.0
CaO, %	3.8	4.3	5.7	4.8	17.0	13.0	3.7	3.5	20.4	30.4	3.5	6.4
SO ₃ , %	0.4	0.3	0.8	0.3	1.7	0.5	0.4	0.1	NR	0.4	NR	NR
MgO, %	0.96	0.88	1.15	0.92	2.23	1.61	1.29	1.17	NR	NR	1.76	2.06
Na ₂ O, %	1.88	1.77	1.61	1.01	0.4	0.5	1.5	1.5	NR	NR	1.36	0.67
K ₂ O, %	0.9	0.8	1.1	1.0	1.44	0.64	0.38	0.43	NR	NR	2.4	1.9
P ₂ O ₅ , %	0.13	0.06	0.04	0.05	0.70	0.30	1.00	0.75	NR	NR	NR	NR
TiO ₂ , %	0.43	0.62	1.17	0.67	1.17	0.50	0.83	0.50	NR	NR	1.00	0.68
As, ppm	12	1	8	1	15	3	6	2	8.4	5.8	110	18
Be, ppm	4.3	3	7	7	3	2	7	5	8.0	7.3	NR	NR
Cd, ppm	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	6.44	1.08	8.0	1.1
Cr, ppm	20	15	50	30	150	70	30	30	206	124	300	152
Cu, ppm	54	37	128	48	69	33	75	40	68	48	140	20
Mg, ppm	267	366	150	700	150	150	100	100	20.0	0.51	0.05	0.028
Mn, ppm	10	10	50	22	70	15	20	10	249	229	298	295
Ni, ppm	70	27	30	30	30	20	70	30	134	62	207	85
Pb, ppm	6.9	0.2	7.9	0.7	18.0	1.0	12.0	1.0	32	8.1	8.0	6.2
V, ppm	90	70	150	85	150	70	100	70	26.5	5.6	25	0.08
Zn, ppm	63	24	00	30	71	27	103	45	341	353	440	260
B, ppm	266	143	200	125	300	70	700	300	352	150	740	100
Co, ppm	7	7	20	12	15	7	15	7	NR	NR	NR	NR
F, ppm	140	50	100	50	610	100	250	85	6.0	3.6	39	20.8
									624	10.6	NR	NR

FA = Fly Ash
BA = Bottom Ash

Source: Reference 118

TABLE 43. COMPARISON OF CONCENTRATIONS OF SPECIES
IN FLY ASH PONDS, BOTTOM ASH PONDS, AND
COMBINED ASH PONDS*

Substance	Fly Ash Pond			Data Pts.
	Range	Avg.		
Arsenic	0.01 - 1.1	0.38		3
Barium	0.2 - 0.3	0.25		2
Cadmium	0.001 - 0.037	0.019		2
Chloride	6 - 7	6.5		2
Chromium	0.02 - 0.067	0.044		2
Copper	0.02 - 2.4	0.91		3
Cyanide	-	-		-
Iron	1.44 - 630	211.12		3
Lead	0.01 - 0.91	0.33		3
Manganese	0.13 - 0.48	0.31		2
Selenium	0.002 - 0.33	0.12		3
Silver	-	-		-
Sulfate	209 - 358	283.5		2
Zinc	0.06 - 2.2	1.26		3

Substance	Bottom Ash Pond			Data Pts.
	Range	Avg.		
Arsenic	0.006 - 0.018	0.012		2
Barium	0.1 - 0.2	0.15		2
Cadmium	0.001 - 0.003	0.002		2
Chloride	7 - 8	7.5		2
Chromium	0.009 - 0.01	0.095		2
Copper	0.041 - 0.065	0.053		2
Cyanide	-	-		-
Iron	5.29 - 5.98	5.64		2
Lead	0.02 - 0.02	0.02		2
Manganese	0.16 - 0.58	0.37		2
Selenium	0.002 - 0.011	0.007		2
Silver	-	-		-
Sulfate	49 - 139	94		2
Zinc	0.09 - 0.14	0.12		2

Substance	Combined Ash Pond			Data Pts.
	Range	Avg.		
Arsenic	0.005 - 0.038	0.038		9
Barium	0.1 - 0.2	0.19		10
Cadmium	0.001 - 0.005	0.002		6
Chloride	3 - 14	7.2		10
Chromium	0.004 - 0.043	0.015		10
Copper	0.01 - 0.08	0.042		10
Cyanide	0.01 - 0.05	0.03		3
Iron	0.23 - 2.3	0.8		10
Lead	0.01 - 0.025	0.014		10
Manganese	0.01 - 0.39	0.09		9
Selenium	0.003 - 0.065	0.016		10
Silver	-	0.01		1
Sulfate	59 - 156	109.7		10
Zinc	0.03 - 0.12	0.053		10

*All concentrations are in mg/L.

Source: Reference 119

TABLE 44. PHYSICAL CHARACTERISTICS OF COAL COMBUSTION WASTES

Parameters	Fly Ash	Bottom Ash and Boiler Slag	FGD Sludge
Specific gravity	2.1-2.6	2.5-2.6	2.3-2.5
Bulk density (g/cm ³)	1.12-1.28	1.15-1.49	1.42 ^a
Permeability (cm/s)	10 ⁻⁶ - 10 ⁻⁵	0.025-0.094	10 ⁻⁴ -10 ⁻⁸
Average moisture content (percent) ^b	15	20	82-185
Compaction indices			
Maximum dry density (g/cm ³)	1.19-1.49	1.16-1.87	1.29-1.52
Optimum moisture content (percent)	19.5-32	13.8-26.2	20-29

^aThe bulk density of FGD sludge depends on the moisture content of the material. The value is for a 50 percent moisture sludge.

^bPercent moisture = $\frac{\text{weight of water}}{\text{weight of dry solids}} \times 100\%$ (ASTM Method D2216, Part 19, 1981)

(ASTM Method D2216, Part 19, 1981).

Source: Reference 120

TABLE 45. SURVEY OF RCRA EP AND ASTM LEACHATE COMPOSITIONS
FOR BOTTOM ASHES BY COAL REGION^a

RCRA Leachates

Trace Element	Rocky Mountain			Coal Province			Gulf Coast		
	Median	Range	N ^b	Median	Range	N ^b	Median	Range	N ^b
Arsenic	.003	<.004-<.001	5	.110	.008-.160	4	.05	.002-.05	5
Barium	.28	.22-<.6	5	.295	.170-.600	4	.4	.34-.6	5
Cadmium	<.0005	<.0008-<.6	5	.0198	.0005-.600	4	.01	.0005-.01	5
Chromium	<.003	.001-.028	5	.036	.003-.2	4	.1	.003-.1	5
Lead	.002	<.002-.009	5	.003	.002-.3	4	.05	.002-.29	5
Mercury	.0008	.0002-.0019	5	.001	.0003-.0013	4	.002	.005-.002	5
Selenium	<.004	<.001-.005	5	.004	.004-.005	4	.01	.004-.01	5
Silver	<.001	<.001-.006	5	.001	.0003-.025	4	.05	.001-.05	5

ASTM Leachates

Trace Element	Rocky Mountain			Coal Province			Gulf Coast		
	Median	Range	N ^b	Median	Range	N ^b	Median	Range	N ^b
Arsenic	.004	.004	2	.024	.005-.043	2	No data		
Barium	.15	.13-.17	2	.1135	.11-.16	2	No data		
Cadmium	.0005	.0005	2	.0005	.0005	2	No data		
Chromium	.12	.10-.14	2	.011	.003-.019	2	No data		
Lead	.002	.002	2	.002	.002	2	No data		
Mercury	.0005	.0005	2	.0005	.0005	2	No data		
Selenium	.004	.004	2	.004	.004	2	No data		
Silver	.001	.001	2	.0015	.001-.002	2	No data		

^aConcentrations are in mg/L.

^bN = Number of data points.

Source: References 76, 79, 83, 121-127

TABLE 46. SURVEY OF RCRA EP AND ASTM LEACHATE COMPOSITIONS FOR FLY ASHES BY COAL REGION^a

RCRA Leachates

Trace Element	Rocky Mountain		Northern Great Plains		Coal Province		Gulf Coast		Interior		Eastern	
	Median	Range	Median	Range	Median	Range	Median	Range	Median	Range	Median	Range
Arsenic	.004	.003-.007	.041	.012-.058	.021	.0001-.05	.0033	.0026-.049	.061	.024-.38		
Barium	1.0	.25-2.3	.21	.17-.27	1.4	.6-2.8	.6	.6	.6	.6		
Cadmium	.0009	.0002-.024	.0003	.0005-.006	.008	.0005-.02	.018	.008-1.6	.004	.0034-.004		
Chromium	.33	.016-.68	.087	.01-.2	.2	.18-.5	.011	.011-.310	.041	.0042-.34		
Lead	.003	.002-.011	.002	.002-.4	.027	.002-.05	.004	.004-.054	.004	.004		
Mercury	.001	.0002-.002	.0014	.004-.002	.002	.0005-.002	.001	.001	.001	.001		
Selenium	.031	.002-.063	.053	.046-.17	.045	.01-.22	.005	.005-.029	.077	.013-.077		
Silver	.0001	.0003-.007	.001	.0003-.03	.0255	.003-.05	.0003	.0003-.0005	.0003	.0003		

ASTM Leachates

Trace Element	Rocky Mountain		Northern Great Plains		Coal Province		Gulf Coast		Interior		Eastern	
	Median	Range	Median	Range	Median	Range	Median	Range	Median	Range	Median	Range
Arsenic	.004	.003-.008	.038	.031-.10	.0035	.003-.004	No data	No data	No data	No data	No data	No data
Barium	.58	.22-3.2	.09	.07-.11	.46	.38-.54	No data	No data	No data	No data	No data	No data
Cadmium	.0005	.002-.0005	.0005	.0005-.006	.0005	.0005	No data	No data	No data	No data	No data	No data
Chromium	.17	.026-.42	.25	.12-.37	.135	.09-.18	No data	No data	No data	No data	No data	No data
Lead	.003	.002-.022	.003	.002-.012	.121	.002-.24	No data	No data	No data	No data	No data	No data
Mercury	.0005	.0013-.0005	.0005	.0005-.0008	.0008	.0008	No data	No data	No data	No data	No data	No data
Selenium	.022	.004-.088	.23	.23-.32	.1975	.005-.39	No data	No data	No data	No data	No data	No data
Silver	.001	.001-.002	.002	.002-.006	.001	.001	No data	No data	No data	No data	No data	No data

^aConcentrations are in mg/L.

^bN = Number of data points.

Sources: References 76, 79, 83, 121-127

transition metals are concentrated in the glass phase of fly ash, while tri-valent and tetravalent metals (Cr, V, Ti, Fe, Ga, and Zr) appear to concentrate in the crystalline mullite phase (128).

Data shown in Table 24 indicate significant variation in trace element composition of the ashes. These variations are due to differences in feed-stock coal as well as enrichment processes during combustion. Variations in fly ash composition have also been related to the particle size of the ash (see Section 3.2.4.2). These parametric differences also affect the leaching of fly ash. Data in Tables 43, 45, and 46 indicate that leachate concentrations in actual fly ash ponds can differ greatly from laboratory leachates. Leachate concentrations are generally higher in actual fly ash ponds than either RCRA or ASTM tests. Regional trends in fly ash leachate concentrations indicate chromium concentrations in the Rocky Mountain Province are frequently high and that western U.S. coal ashes generally produce more alkaline leachates than eastern coal ashes.

3.4.3.4 Flue Gas Desulfurization Wastes

Flue gas desulfurization can be accomplished through a variety of gas scrubbing processes. Typically, an alkaline liquid or solid is intimately contacted with the gas stream to remove the acid sulfur gases. The scrubber liquor or solid reacts with the sulfur dioxide to form a sulfite salt. The alkalinity required to drive the reaction toward the product species is supplied by the reagent—lime, limestone, alkaline fly ash, or soda ash.

The three major solid phases in these wastes are: $\text{CaSO}_3 \cdot 1/2\text{H}_2\text{O}$, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, and $(X)\text{CaSO}_3 \cdot (1-X)\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$. The scrubber waste will also contain small amounts of entrained fly ash and volatile trace elements absorbed from the flue gas.

Ranges of trace element and major species concentrations in sludge liquors from three earlier studies are given in Table 47. Locations and coal types were not given in these studies. Laboratory column leaching studies of

TABLE 47. RANGES OF CONCENTRATIONS IN FGD SLUDGE LIQUORS AND LEACHATES

Species	Ref. 124			Ref. 122			Ref. 130			All Sources		
	Range, mg/l	Mean, mg/l	Median, mg/l	Range, mg/l	Median, mg/l	Range, mg/l	Range, mg/l	Median, mg/l	Range, mg/l	Range, mg/l	Range, mg/l	Range, mg/l
Aluminum	0.09 to 2.9	—	—	—	—	—	0.03 to 0.3	—	0.03 to 0.3	0.03 to 0.3	0.03 to 0.3	0.03 to 0.3
Antimony	0.004 to 0.3	0.2	1.2	—	—	—	0.09 to 2.3	—	0.09 to 2.3	0.09 to 2.3	0.09 to 2.3	0.09 to 2.3
Arsenic	0.0006 to 0.18	0.009	0.02	—	—	—	<0.004 to 0.3	—	<0.004 to 0.3	<0.004 to 0.3	<0.004 to 0.3	<0.004 to 0.3
Beryllium	—	0.013	0.014	—	—	—	<0.0006 to 0.14	—	<0.0006 to 0.14	<0.0006 to 0.14	<0.0006 to 0.14	<0.0006 to 0.14
Boron	0.9 to 46	—	41	—	—	—	8.0 to 46	—	8.0 to 46	8.0 to 46	8.0 to 46	8.0 to 46
Cadmium	0.002 to 0.044	0.032	—	—	—	—	0.004 to 0.11	—	0.004 to 0.11	0.004 to 0.11	0.004 to 0.11	0.004 to 0.11
Chromium	0.005 to 0.4	0.08	0.02	—	—	—	0.01 to 0.5	—	0.01 to 0.5	0.01 to 0.5	0.01 to 0.5	0.01 to 0.5
Cobalt	0.1 to 0.7	—	0.35	—	—	—	0.1 to 0.17	—	0.1 to 0.17	0.1 to 0.17	0.1 to 0.17	0.1 to 0.17
Copper	0.002 to 0.6	0.20	0.015	—	—	—	0.002 to 0.6	—	0.002 to 0.6	0.002 to 0.6	0.002 to 0.6	0.002 to 0.6
Fluoride	0.7 to 3.0	1.5	3.2	—	—	—	0.7 to 3.0	—	0.7 to 3.0	0.7 to 3.0	0.7 to 3.0	0.7 to 3.0
Iron	0.02 to 8.1	—	0.026	—	—	—	0.02 to 8.1	—	0.02 to 8.1	0.02 to 8.1	0.02 to 8.1	0.02 to 8.1
Lead	0.001 to 0.4	0.016	0.12	—	—	—	0.01 to 0.4	—	0.01 to 0.4	0.01 to 0.4	0.01 to 0.4	0.01 to 0.4
Manganese	0.007 to 2.5	0.74	0.17	—	—	—	0.007 to 2.5	—	0.007 to 2.5	0.007 to 2.5	0.007 to 2.5	0.007 to 2.5
Mercury	0.0004 to 0.07	<0.01	0.001	—	—	—	0.0004 to 0.07	—	0.0004 to 0.07	0.0004 to 0.07	0.0004 to 0.07	0.0004 to 0.07
Molybdenum	0.07 to 6.3	—	5.3	—	—	—	0.91 to 6.3	—	0.91 to 6.3	0.91 to 6.3	0.91 to 6.3	0.91 to 6.3
Nickel	0.005 to 1.5	0.09	0.13	—	—	—	0.005 to 1.5	—	0.005 to 1.5	0.005 to 1.5	0.005 to 1.5	0.005 to 1.5
Selenium	0.001 to 2.2	0.14	0.11	—	—	—	<0.001 to 2.2	—	<0.001 to 2.2	<0.001 to 2.2	<0.001 to 2.2	<0.001 to 2.2
Silver	0.005 to 0.6	—	—	—	—	—	0.005 to 0.6	—	0.005 to 0.6	0.005 to 0.6	0.005 to 0.6	0.005 to 0.6
Tin	3.1 to 3.5	—	—	—	—	—	3.1 to 3.5	—	3.1 to 3.5	3.1 to 3.5	3.1 to 3.5	3.1 to 3.5
Uranium	—	—	—	—	—	—	—	—	—	—	—	—
Vanadium	0.001 to 0.67	—	—	—	—	—	0.001 to 0.67	—	0.001 to 0.67	0.001 to 0.67	0.001 to 0.67	0.001 to 0.67
Zinc	0.03 to 2.0	0.18	0.046	—	—	—	0.01 to 0.27	—	0.01 to 0.27	0.01 to 0.27	0.01 to 0.27	0.01 to 0.27
Alkalinity, as CaCO ₃	—	—	—	—	—	—	—	—	—	—	—	—
Calcium	—	—	—	—	—	—	—	—	—	—	—	—
Chloride	—	—	—	—	—	—	—	—	—	—	—	—
Chloride	—	—	—	—	—	—	—	—	—	—	—	—
Magnesium	—	—	—	—	—	—	—	—	—	—	—	—
pH	—	—	—	—	—	—	—	—	—	—	—	—
Potassium	—	—	—	—	—	—	—	—	—	—	—	—
Sodium	—	—	—	—	—	—	—	—	—	—	—	—
Sulfite	—	—	—	—	—	—	—	—	—	—	—	—
Sulfate	—	—	—	—	—	—	—	—	—	—	—	—
TDS	—	—	—	—	—	—	—	—	—	—	—	—
Conductance, mho/cm	—	—	—	—	—	—	—	—	—	—	—	—
Turbidity, JNU	—	—	—	—	—	—	—	—	—	—	—	—

^aSufficient data were not available for the meaningful calculation of a mean.

^bThe highest levels shown reflect single measurements on an unashed double-alkali filter cake.

^cLevels of soluble chloride components in sludges are dependent upon the chloride-to-sulfite ratio in the coal. The highest levels shown are single measurements for a western limestone scrubbing system.

Sources: References 124, 129, 130

calcium-based FGD sludges have shown that the first few pore volumes of leachate contain elevated concentrations from the entrained scrubber liquor (83). Subsequent leachates level off to a dissolved solids concentration controlled by the solubility of the calcium sulfite, sulfate, or carbonate.

3.4.4 Disposal and Mechanisms of Contaminant Transport

There are two basic types of disposal systems used for coal wastes: wet (impoundment or ponding) and dry (landfilling). In wet disposal systems, the coal wastes are transported and deposited at the disposal site in a fluid state. Dry disposal systems use processing steps so that the wastes are handled and disposed of as a solid material. Both the quality and quantity of leachate can be largely affected by the disposal alternative chosen. Common solid waste management options for large volume utility wastes are summarized in Table 48.

Impoundments (ponds) containing liquids or semi-liquid wastes are not permanent disposal facilities. Prior to closure, an impoundment must either be covered properly or the solid residues removed from the impoundment. Because the wastes are liquids, the potential for migration of contaminants to ground water exists. Therefore, controls must be exercised to contain the wastes or ensure that their migration will not affect water resources. While wet disposal systems are often advantageous, they are not universally applicable to all disposal of utility wastes. For example, climatic conditions, regulatory requirements, and/or site related constraints may make wet disposal undesirable or uneconomic. The most common problem with pond disposal is the absence of suitable land area of sufficient size in close proximity to the plant for an impoundment.

In dry disposal systems, the waste is either deposited as a solid material or a chemically stabilized material which will rapidly solidify. This stabilization may involve blending dry wastes with wet wastes. Since the wastes are "dry" and compacted, landfill disposal uses less area and generally produces less risk of leachate penetration than impoundments. Rain falling on

TABLE 48. SOLID WASTE MANAGEMENT OPTIONS FOR THE UTILITY INDUSTRY

Solid Waste Management Options	Solid Wastes	Comments
LAND DISPOSAL		
Nonhazardous landfill, minefill	Ashes, FGD sludge, comixes, water treatment sludges, coal preparation wastes	Generally the largest volume of wastes will be landfilled or mine-filled.
Hazardous landfill	Wastewater treatment sludges, spend filter media	Some form of pretreatment, either stabilization or fixation, will generally be required prior to land disposal of sludges.
Nonhazardous impoundment (pond)	Ashes, FGD sludge, plant run-off, demineralizer regenerant coal preparation wastes	Some plants may choose to dispose of their coal ashes and sludges by wet methods. This will result in larger volumes and greater potential for leaching over dry land disposal.
Hazardous impoundment (pond)	Wastewater treatment sludges, water treatment brines, metal cleaning wastes, equipment cleaning wastes, laboratory wastes.	Hazardous impoundments are only considered storage facilities. The residue must be removed or buried for closure.
REUSE/RECLAIM		
Reuse	Ash, FGD sludge, sulfur	Coal ashes may be used as aggregate, road base or cement additive. Certain FGD sludges are regenerable (sulfur), and other gas cleaning processes can produce sulfur as a by-product.

a well-constructed landfill is diverted rather than impounded; however, diversion and drainage systems have to be properly designed. The absence of pooled water on top of the waste body will substantially reduce the quality of leachate. Reclamation is also somewhat easier with landfills.

Contaminants from solid utility wastes may stay in the waste body, migrate to the soil and remain, migrate to ground water, migrate to surface water, or migrate to the air. The scope of this work covers existing literature on leaching only; however, to define realistic environmental effects utility wastes will produce, it is also necessary to understand site-specific attenuation of waste leachates by local soils. In general, coal waste leachate may contain elevated levels of dissolved solids, including sulfate, chloride, selenium, and chromium, above the concentrations found in associated aquifers. These constituents vary widely in their geochemical behavior specifically in their interactions with soil-rock media. Mechanisms for attenuation, although not fully understood, are believed to involve ion exchange, adsorption/desorption, precipitation/dissolution and diffusion/dispersion.

The principal method of migration to the ground water is through dissolution into adherent liquor and infiltrating water. Contaminants within the liquid phase may then migrate by diffusion into adjacent water and/or by displacement with infiltrating water. The chemistry of these mechanisms is just beginning to be fully understood. Prior to contacting the ground water, contaminants usually must migrate through hydrogeologically unsaturated soils where some degree of attenuation will take place. Even after the contaminants enter the ground water, soil attenuation mechanisms will continue to reduce the contaminant levels.

There currently exist some empirical data on the attenuation of utility waste leachates and experimental data of attenuation in ideal systems through which theoretical models have been developed (74, 131, 132). However, the existing empirical and theoretical models do not cover the broad range of leachate and soil/rock environments possible nor have they been adequately verified under laboratory and field conditions. The primary attenuation mechanisms are:

Ion Exchange. Concentrations of trace metals in aqueous systems are often not dictated by their mineral solubilities but by their surface interactions with solid sediments, soils, or rocks. The attenuation mechanisms of ion exchange and adsorption become extremely important in systems containing colloids or small particles which will have large available surface areas. Ion exchange is defined as the predominant mechanism of surface sorption on materials having a fixed charge (e.g., clays), and adsorption will be defined as the principal mechanism on materials with surface potential dependent upon the material and solution composition (e.g., iron and manganese hydroxides).

Adsorption. Adsorption of metal ions on a solid surface may be a reversible or non-reversible reaction. Layers of hydration around the metal ion remain intact even after adsorption to the solid surface. Some ionic species have a specific affinity for the surface atoms and adsorb out of all proportion to their concentration in solution. The controlling mechanism appears to be the hydrolysis of the metal ion and the subsequent surface adsorption of the hydrolyzed species.

Precipitation. Precipitation broadly refers to any mechanism which results in a chemical species crossing from the liquid to solid phase. However, it is generally defined as primary precipitation where a metal forms an insoluble compound with other species in solution.

Within the relatively low ionic strength range found in coal waste leachates (<1.0 M), most extensions of the Debye-Huckel equations will accurately estimate aqueous phase activities. Precipitation mechanisms are undoubtedly the best understood and have the most likely developed models of any of the attenuation processes.

Hydrodynamic Dispersion. In ground water hydrology, the spreading process is termed hydrodynamic dispersion. Solute spreading parallel to the direction of bulk flow is termed longitudinal dispersion. Spreading which is perpendicular to fluid flow is termed transverse dispersion. Hydrodynamic dispersion is the sum of two processes, mechanical dispersion and molecular diffusion which are described below.

Mechanical Dispersion. Mechanical dispersion is viewed from both microscopic and macroscopic perspectives. Microscopic refers to analysis of processes on the scale of individual grains and pore openings, while macroscopic refers to analysis of processes which are "averaged" for a representative bulk volume of porous media. Microscopic (mechanical) dispersion is believed to be caused by variations in individual pore channel fluid velocities, by variations in fluid velocities between different pore channels, and by pore channel "tortuosity," branching, and interfingering. Macroscopic (mechanical) dispersion may be caused by heterogeneities in the porous media on a macroscopic scale.

Molecular Diffusion. Solutes under the influence of their kinetic activity move in the direction of the concentration gradient. Molecular diffusion occurs even in the absence of fluid movement. For solutions, Fick's first law relates solute mass flux through given cross-sectional areas and concentration gradients using a diffusion coefficient.

Geochemical and Hydrodynamic Factors Affecting Attenuation Mechanisms. Major geochemical controls on the degree of attenuation in a leachate system include the solution pH, redox potential, ionic strength, and presence of complexing ligands and organic molecules. Also, the type of soil/rock media, temperature, hydraulic head, and flow regime will all impact the mechanisms and rates of attenuation. The types of soil/rock media which will most likely enhance attenuation at the pH and Eh conditions of coal waste leachate are iron and manganese hydroxides, clays, organic soils, and minerals with functional groups which will specifically adsorb certain trace metals. Chemical kinetics may also affect attenuation.

3.4.5 Summary and Conclusions

Available literature on leaching of coal wastes indicates that the chemistry and prediction of leachate quality and quantity is a complicated matter. While experimental laboratory techniques to model field leaching have been developed and theoretical computer models are available, quantifiable correlations have been restricted mostly to relationships between waste composition

and leachate composition. While information from the coal data base provides necessary mass balance information, it is not possible to use these data alone to predict waste leachate properties due to the complex matrix of factors affecting leaching. Furthermore, definition of the leachate properties must be augmented by the leachate attenuation behavior with specific soil/rock media to determine the impact that the waste leachate will eventually have on ground water. Literature further indicates that trace metal behavior in leachates varies more than major constituent composition (sulfate) due to feedstock variation and process effects. While the leaching behavior of some major species may be rather predictable, trace element behavior is not. Some of these variations may be attributed to analytical and extraction techniques.

Correlation of large leachate data bases documented in existing literature with the coal data base could possibly provide useful information for ranges of leaching behavior for major constituents. The reliability of these correlations for coals mined in different coal provinces will need to be defined. Further laboratory tests are necessary to determine average leachability factors for trace elements listed in the coal data base for each coal region. Definition of environmental impacts from coal waste disposal will also require information about the disposal area as well as the leachate quality.

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SECTION 4

STATISTICAL ANALYSIS OF EXISTING PARTITIONING DATA

As indicated in Section 3, a number of studies have already been completed on the partitioning of sulfur and trace elements during coal preparation and combustion processes. This section discusses the results of statistical analyses undertaken using data from these earlier studies to identify the effect of coal properties and other variables on partitioning in the two processes.

4.1 COAL PREPARATION

4.1.1 Laboratory Gravity Separation Data

Data on trace element partitioning during gravity separation have been developed by ISGS (1), DOE (2), and BCR (3, 4). A total of 45 coals have been evaluated—23 from Appalachia, 13 from the Illinois Basin, and 9 from the western U.S. Summary information on each of these coals is presented in Table 49.¹⁰ General conclusions reached from these studies are presented in Sections 2.3.1 and 3.1.3.

The least extensive of the three studies relative to the number of elements evaluated is that of DOE which was limited to Cd, Cr, Cu, F, Hg, Mn, Ni, and Pb. DOE also collected data on ash and sulfur removal from each coal, but did not include this data in the final report. Major ash constituents were not determined. The most extensive sample characterizations were those of ISGS which analyzed up to 54 major and trace elements, proximate analysis, forms of sulfur, and heat content. BCR analyzed for 26 elements, sulfur forms, and percent ash.

¹⁰BCR Sample 5R (a low-ash, subbituminous coal from the Hanna 60 seam in Carbon County, Wyoming) was deleted from the data set used in this study due to poor material balance closures for several elements (removals <0% and >100%).

TABLE 49. DESCRIPTION OF 44 COALS SUBJECTED TO THE GRAVITY SEPARATION

ID	REGION	PROVINCE	FORMATION	SEAM	STATE	COUNTY	RANK	TOP_SIZE	BOT_SIZE	SG
DOE1	4N	AP	MONONGAHEL	PITTSBURGH	PA	ALLEGHENY	HVAB	0.05	0.00	1.60
DOE2	4N	AP	MONONGAHEL	WAYNESBURG	OH	HV B	HV B	0.05	0.00	1.60
10R	4N	AP	SEWICKLEY	SEWICKLEY	OH	NOBLE	HVBB	1.25	0.02	1.55
18892	4N	AP	MONONGAHEL	PITTSBURGH	WV		HVBB	0.38	0.02	1.60
19R	4N	AP	MONONGAHEL	PITTSBURGH	PA	WASHINGTON	HVAB	1.25	0.02	1.55
22R	4N	AP	MONONGAHEL	SEWICKLEY	PA	GREENE	HVAB	1.25	0.02	1.60
23R	4N	AP	MONONGAHEL	PITTSBURGH	OH	BEAUMONT	HVBB	1.25	0.02	1.60
24R	4N	AP	MONONGAHEL	PITTSBURGH	WV	HARRISON	HVAB	1.25	0.02	1.60
9R	4N	AP	MONONGAHEL	PITTSBURGH	WV	HARRISON	HVAB	1.25	0.02	1.55
DOE3	4N	AP	ALLEGHENY	U FREEPORT	MD	GARRETT	HV B	0.05	0.00	1.60
1R	4N	AP	ALLEGHENY	L FREEPORT	PA	INDIANA	HVBB	1.25	0.02	1.55
20R	4N	AP	ALLEGHENY	L KITTING	PA	CAMBRIA	LVB	1.25	0.02	1.55
21R	4N	AP	ALLEGHENY	L KITTING	PA	CAMBRIA	HVB	1.25	0.02	1.60
8R	4N	AP	ALLEGHENY	L KITTING	WV	NICHOLAS	HVAB	1.25	0.02	1.55
DOE4	4S	AP	KANAWHA	HAZARD 4	KY	BELL	HV B	0.05	0.00	1.60
11R	4S	AP	POCONONTAS	POCONONTAS 3	WV	MCDONELL	LVB	1.25	0.02	1.55
12R	4S	AP	KANAWHA	STOCKTON	WV	LOGAN	HVAB	1.25	0.02	1.55
13R	4S	AP	NEW RIVER	SEWELL	WV	RALEIGH	HVB	1.25	0.02	1.55
14R	4S	AP	NEW RIVER	SEWELL	AL	WALKER	HVAB	1.25	0.02	1.55
17R	4S	AP	KANAWHA	L ELKHORN	VA	WISE	HVAB	1.25	0.02	1.55
18R	4S	AP	KANAWHA	V ELKHORN 3	KY	KNOX	HVAB	1.25	0.02	1.55
18889	4S	AP	NEW RIVER	BLUE CREEK	AL			0.38	0.02	1.60
18890	4S	AP	POCONONTAS	POCONONTAS 4	WV			0.38	0.02	1.60
DOE5	6	IN	ALLEGHENY	ILLINOIS 6	IL	PERRY	HVBB	0.05	0.00	1.60
DOE6	6	IN	ALLEGHENY	ILLINOIS 5	IL	PERRY	HV B	0.05	0.00	1.60
DOE7	6	IN	ALLEGHENY	DEKOVEN	KY	OHIO	HV B	0.05	0.00	1.60
15R	6	IN	ALLEGHENY	ILLINOIS 5	KY	MUHLBURG	HVBB	1.25	0.02	1.55
16R	6	IN	ALLEGHENY	ILLINOIS 5	IL	FULTON	HVCB	1.25	0.02	1.55
16370	6	IN	ALLEGHENY	DAVIS	IL			0.38	0.02	1.60
18972	6	IN	ALLEGHENY	DEKOVEN	IL			0.38	0.02	1.60
18121	6	IN	ALLEGHENY	ILLINOIS 6	IL			0.38	0.02	1.60
18133	6	IN	ALLEGHENY	ILLINOIS 2	IL			0.38	0.02	1.60
18362	6	IN	ALLEGHENY	ILLINOIS 6	IL			0.38	0.02	1.60
2R	6	IN	ALLEGHENY	ILLINOIS 6	IL			0.38	0.02	1.60
25R	6	IN	ALLEGHENY	ILLINOIS 6	IL	FRANKLIN	HVBB	1.25	0.02	1.55
26R	6	IN	ALLEGHENY	ILLINOIS 6	IL	WILLIAMSON	HVBB	1.25	0.02	1.60
3R	12	NGF	PALEOCENE	BEULAH-2AP	MD	HOPKINS	HVBB	1.25	0.02	1.60
6R	18	RM	CRETACEOUS	ROSEBUD	MT	MERCER	LIGA	1.25	0.02	1.55
7R	19	RM	CRETACEOUS	ADRIANVILLE 1	WY	ROSEBUD	SUBB	1.25	0.02	1.55
DOE8	BLMS	RM	CRETACEOUS	ESTIL GAT D	UT	LINCOLN	SUBA	1.25	0.02	1.55
DOE9	21	RM	CRETACEOUS	BLACK MESA	AZ	CARON	HVAB	1.25	0.02	1.55
17014	BLMS	RM	CRETACEOUS	SAN JUAN B	NM	NAVAJO	SUB	0.38	0.00	1.60
DOE10	24	RM	CRETACEOUS	BLACK MESA	AZ	SAN JUAN	SUB	0.38	0.00	1.60
			CRETACEOUS	ROCK SPRING	WY	SHEETWATER	HVCB	0.05	0.00	1.60

A summary of element removal data for major and trace species from these coals is presented in Table 50. Data for elemental removals from each coal are presented in Appendix II. The table is subdivided into six regions—the Monongahela, Allegheny, and Pottsville units of Appalachia, the Illinois Basin, the Northern Great Plains, and the Rocky Mountains. The subdivision of the Appalachian Province into three geologic units is based on the differences in depositional conditions believed to have existed during each of these periods and the resulting impact on the coals. These geologic units are also roughly equivalent to the subdivision of the Appalachian Province into a southern region consisting of southern West Virginia and states to the south (which produce coals from the Pottsville Group) and a northern region consisting of the remainder of the province (which produce primarily from the Monongahela Group and Allegheny Formation). Means and standard deviations are computed to each region and element. Element removal reported in Table 50 is computed from analytical data using the following formula:

$$\% \text{REMOVAL} = 100 - (\text{YIELD} \times \text{CONC}_{\text{CC}} / \text{CONC}_{\text{RC}}),$$

where YIELD = Weight percent recovered as cleaned coal, CONC_{CC} = elemental concentration in cleaned coal, and CONC_{RC} = elemental concentration in raw coal.

These data indicate that the Allegheny Formation coals have the greatest removal potential for most trace elements and that the Rocky Mountain coals have the least potential. Due to the limited number of samples available from each region (especially from the Northern Great Plains Province), the validity of the computed values is subject to considerable statistical uncertainty. However, sulfur reduction data for these samples compare favorably with the regional trends obtained by Cavallaro et al. (5), thus suggesting that the computed values for trace element removal may reasonably reflect the regional values.

TABLE 50. REGIONAL SUMMARY FOR REMOVAL OF MAJOR AND TRACE ELEMENT SPECIES BY GRAVITY SEPARATION OF 44 U.S. COALS^a

	Appalachian Province			Interior Province	N. Great Plains Province	Rocky Mountain Province
	Monongahela	Allegheny	Pottsville			
Number of samples	9	5	9	13	2	6
Sulfur (S), total	29 $\pm$ 15	53 $\pm$ 17	27 $\pm$ 18	38 $\pm$ 9	50 $\pm$ 8	11 $\pm$ 8
Sulfur (S), pyritic	40 $\pm$ 20	66 $\pm$ 15	52 $\pm$ 22	57 $\pm$ 15	53 $\pm$ 9	32 $\pm$ 23
Sulfur (S), organic	4 $\pm$ 4	14 $\pm$ 9	9 $\pm$ 8	0 $\pm$ 5	15 $\pm$ 3	-9 $\pm$ 13
Ash	52 $\pm$ 23	73 $\pm$ 12	74 $\pm$ 20	48 $\pm$ 15	41 $\pm$ 8	35 $\pm$ 23
Silicon (Si)	57 $\pm$ 27	78 $\pm$ 12	79 $\pm$ 15	47 $\pm$ 22	52 $\pm$ 4	22 $\pm$ 30
Aluminum (Al)	52 $\pm$ 28	72 $\pm$ 13	71 $\pm$ 21	42 $\pm$ 21	36 $\pm$ 2	14 $\pm$ 20
Calcium (Ca)	55 $\pm$ 26	51 $\pm$ 14	56 $\pm$ 26	55 $\pm$ 34	13 $\pm$ 7	8 $\pm$ 20
Magnesium (Mg)	57 $\pm$ 29	80 $\pm$ 11	79 $\pm$ 17	53 $\pm$ 25	16 $\pm$ 1	12 $\pm$ 20
Sodium (Na)	48 $\pm$ 29	72 $\pm$ 11	70 $\pm$ 25	44 $\pm$ 28	18 $\pm$ 9	12 $\pm$ 19
Potassium (K)	62 $\pm$ 27	82 $\pm$ 12	81 $\pm$ 19	47 $\pm$ 27	59 $\pm$ 10	34 $\pm$ 46
Iron (Fe)	45 $\pm$ 20	76 $\pm$ 5	65 $\pm$ 24	61 $\pm$ 19	68 $\pm$ 15	28 $\pm$ 23
Manganese (Mn)	54 $\pm$ 24	78 $\pm$ 13	75 $\pm$ 24	57 $\pm$ 25	31 $\pm$ 16	37 $\pm$ 38
Titanium (Ti)	58 $\pm$ 25	71 $\pm$ 14	70 $\pm$ 23	42 $\pm$ 24	42 $\pm$ 6	15 $\pm$ 23
Phosphorus (P) ^b	56 $\pm$ 23	57 $\pm$ 25	64 $\pm$ 25	67 $\pm$ 44	24 $\pm$ 6	11 $\pm$ 8
Antimony (Sb) ^b	34 $\pm$ 19	32 $\pm$ 2	28 $\pm$ 13	17 $\pm$ 16	43 $\pm$ 22	24 $\pm$ 27
Arsenic (As) ^b	53 $\pm$ 22	77 $\pm$ 11	75 $\pm$ 10	61 $\pm$ 20	69 $\pm$ 11	32 $\pm$ 23
Beryllium (Be) ^b	37 $\pm$ 23	44 $\pm$ 12	43 $\pm$ 20	22 $\pm$ 10	12 $\pm$ 6	-5 $\pm$ 31
Boron (B) ^b	20 $\pm$ 21	62 $\pm$ —	30 $\pm$ 6	10 $\pm$ 6	—	1 $\pm$ —
Cadmium (Cd)	43 $\pm$ 20	48 $\pm$ 12	54 $\pm$ 20	71 $\pm$ 22	33 $\pm$ 13	35 $\pm$ 26
Chromium (Cr)	41 $\pm$ 24	57 $\pm$ 17	65 $\pm$ 23	37 $\pm$ 18	34 $\pm$ 13	24 $\pm$ 15
Cobalt (Co) ^b	46 $\pm$ 30	69 $\pm$ 15	39 $\pm$ 25	39 $\pm$ 20	—	3 $\pm$ —
Copper (Cu)	46 $\pm$ 22	61 $\pm$ 14	48 $\pm$ 20	35 $\pm$ 20	28 $\pm$ 3	14 $\pm$ 11
Fluorine (F) ^b	51 $\pm$ 25	66 $\pm$ 16	80 $\pm$ 12	46 $\pm$ 20	28 $\pm$ 11	24 $\pm$ 15
Lead (Pb)	49 $\pm$ 25	74 $\pm$ 10	60 $\pm$ 23	48 $\pm$ 19	41 $\pm$ 4	34 $\pm$ 18
Mercury (Hg)	36 $\pm$ 14	58 $\pm$ 8	51 $\pm$ 20	34 $\pm$ 22	36 $\pm$ 21	25 $\pm$ 20
Nickel (Ni)	43 $\pm$ 20	52 $\pm$ 7	46 $\pm$ 23	31 $\pm$ 18	5 $\pm$ 2	15 $\pm$ 15
Selenium (Se) ^b	39 $\pm$ 18	65 $\pm$ 13	43 $\pm$ 17	35 $\pm$ 16	46 $\pm$ 13	15 $\pm$ 15
Vanadium (V) ^b	41 $\pm$ 23	59 $\pm$ 16	60 $\pm$ 28	29 $\pm$ 15	16 $\pm$ 13	8 $\pm$ 21
Zinc (Zn) ^b	50 $\pm$ 28	65 $\pm$ 10	69 $\pm$ 24	57 $\pm$ 27	47 $\pm$ 22	34 $\pm$ 30

^aWhole-coal basis; mean $\pm$ standard deviation.

^bMean and standard deviation based on less than total number of samples due to lack of data; see Appendix II.

4.1.2 Statistical Analysis of Gravity Separation Data

The data on trace element partitioning during gravity separation were analyzed using several statistical techniques, including linear correlations, cluster analysis, discriminant analysis, principal components, step-wise regression, and regression of the logit transform of the data. Statistical routines used for these analyses are part of the Statistical Analysis System (SAS). The results obtained using linear correlations and regression of the logit transformed data were the most productive and are detailed in the following. Results of the other techniques are briefly summarized where appropriate.

Correlation analysis was used as an initial screening tool to judge the similarity of the data with previous studies and to assist in defining the best approach for further data analysis. Mineral suites identified from correlation analysis of the feed coal (i.e., elements with correlation coefficients (CC) ≥ 0.70) were the trace element sulfides (As, Cd, Pb, Sb, and Zn), the clays (Al, K, Si, Ti, plus the trace elements Co, Cr, and V), and pyrite (Fe and S). Fluorine correlated with elements in several mineral suites—the clays (Al, K, Si, Ti, and Cr), the chalcophiles Cu and Ni, and the element Be. Correlation coefficients between all other elements were less than 0.70. Due to the absence of major element data in the DOE studies, correlations between trace elements and major ash constituents were limited to the 35 coals analyzed by ISGS and BCR.

Similar correlation tests were conducted on the data for trace element removal. A large number of elements showed coefficients greater than 0.70 and appeared to suggest the importance of ash removal rather than removal of any individual element. Every element examined except sulfur and the chalcophiles As, Cd, Hg, and Sb correlated with total ash removal at greater than 0.70. While no correlations between either total sulfur or pyritic sulfur and an individual element exceeded 0.70, the chalcophiles As, Hg, and Fe exceeded 0.50 with pyritic sulfur and As, Co, Hg, Pb, Se, and Fe exceeded 0.50 with total sulfur. Efforts to correlate percent removal of an element with the quantity of that element in the feed coal found that, except for elements

occurring in the clays, no strong correlations existed. A logical interpretation of this finding is that the abundance of clays, rather than the abundance of the trace element itself, determines the extent of removal possible. That is, removal of a trace element such as Cr will correlate with quantity of Cr in the feed coal ($CC=0.75$) because of the occurrence of Cr in the clays. On the other hand, the removal of an element such as As which occurs primarily as a sulfide is almost totally independent of the amount of As in the feed coal ($CC=0.07$).

Use of principal components analysis with both the feed coal and the removal data yielded similar results. Analysis of the coal feed data resulted in identification of three principal groups:

- Group 1 consisting of Al, K, Si, Ti, Cr, V, and ash which are assumed to represent the clay minerals;
- Group 2 consisting of As, Cd, Pb, and Zn assumed to represent the trace element sulfides; and
- Group 3 consisting of Ca, Fe, and Mg assumed to represent the carbonates.

Analysis of the removal data yielded two groups:

- Group 1 consisting of Al, K, Na, Si, Ti, Be, Cr, Cu, Mn, Ni, V, and ash which were assumed to represent the elements whose removal is associated with the removal of ash; and
- Group 2 consisting of Fe, As, Hg, and S assumed to be pyritic sulfur removal.

Note that the removal of the chalcophiles Cu and Ni with the ash and the inclusion of only As and Hg as trace elements removed with pyritic sulfur

agrees with the detailed microscopic studies and elemental associations presented in Section 2.

Cluster and discriminant analysis techniques were used to examine the data to determine whether regional trends existed in the data. That is, do the data for coals from a given region exhibit stronger similarities with each other than with coals from other regions? The regions used for this analysis were the Monongahela, Allegheny, and Pottsville units in the Appalachian Province, the Interior Province, the Northern Great Plains Province, and the Rocky Mountain Province. Two sets of data were used. The first set was designed to examine the extent to which coals could be distinguished based solely on their trace element composition plus the total quantity of ash and sulfur in the coal. This data set consisted of the seven trace elements for which all 44 samples reported values (Cd, Cr, Cu, Hg, Mn, Ni, and Pb), ash, and total sulfur. The second data set contains data on the total ash chemistry of the coal; parameters used were the major ash forming elements, the above seven trace elements, plus As, Be, Se, V, and Zn. Data in the second data set consisted of the 34 samples analyzed by the ISGS and BCR.

Clustering techniques were used to identify individual coal samples which exhibit similar characteristics and to assign these samples to the same cluster. Sets of clusters are generated from the data base on the "closeness" of individual data points and previously formed clusters. Prior knowledge of which data points "should" belong together (e.g., that two of the samples come from the same region or seam) is not used in the analysis. Using trace element data for all 44 samples, cluster analysis was unable to accurately group these coals into the above six regions. Analysis of the expanded ash chemistry data set was not conducted.

Discriminant analysis differs from cluster analysis in that prior knowledge of which data points "should" be similar is used to generate a regression equation based on the data points in each group. Based on this equation, discriminant analysis is used to evaluate whether each individual data point is closer to the group from which it comes or to another group. Using the

first data set (Cd, Cr, Cu, Hg, Mn, Ni, Pb, plus ash and total sulfur), discriminant analysis of the coal feed and element removal data correctly assigned 34 of 44 and 37 of 44 data points among the six groups, respectively (Table 51).

TABLE 51. DISCRIMINANT ANALYSIS RESULTS FOR GRAVITY SEPARATION DATA SET I

Sample	Feed ^a	Removal ^b	From Group	To Group
DOE9	X		Rocky Mountain	Northern Great Plains
DOE10	X		Rocky Mountain	Northern Great Plains
8R	X	X	Allegheny	Pottsville
20R	X	X	Allegheny	Northern Great Plains
DOE1	X		Monongahela	Pottsville
19R	X		Monongahela	Pottsville
22R		X	Monongahela	Allegheny
24R		X	Monongahela	Interior
13R		X	Pottsville	Allegheny
18889	X	X	Pottsville	Rocky Mountain
DOE5	X		Interior	Monongahela
DOE7	X		Interior	Monongahela
2R	X		Interior	Monongahela
26R	X		Interior	Monongahela
15R		X	Interior	Monongahela

^aSamples misassigned based on feed coal data.

^bSamples misassigned based on element removal data.

Summary statistics on the number of samples and the incorrect assignments for each group are: Northern Great Plains (two samples, 0 incorrectly assigned based on feed coal data, 0 incorrectly assigned based on element removal data) Rocky Mountain (6, 2, 0), Allegheny (5, 1, 2), Monongahela (9, 2, 2), Pottsville (9, 1, 2), and Interior (13, 4, 1).

Discriminant analysis using the second data set reflecting total ash composition resulted in the proper assignment of 34 out of 35 samples for both the feed and removal data. The only misassigned points were sample 2R which was assigned to the Monongahela rather than to the Interior group using the feed data and 19R which was assigned to the Pottsville rather than to the Monongahela group based on the removal data. Summary statistics using the

above convention were Northern Great Plains (2, 0, 0), Rocky Mountain (3, 0, 0), Allegheny (4, 0, 0), Monongahela (7, 0, 1), Pottsville (8, 0, 0), and Interior (10, 1, 0).

The combination of these two approaches—cluster analysis and discriminant analysis—suggests that while significant differences can exist between individual samples even when taken from the same seam or region, regional trends do exist in the data which can assist in determining the likely origin of an individual sample. These trends appear to be more pronounced when total ash composition data are used.

Regression analysis was used to develop estimates of trace element reduction potential during coal cleaning. Based on the results from correlation and discriminant analysis discussed above, ash and total sulfur removal were used as the independent variables with the removal of trace elements as the dependent variable. Use of Al as an estimate of ash, Fe as an estimate of sulfide, and Ca as an estimate of carbonate content was examined, but provided no better results than use of ash and sulfur content; the DOE data could not be used in this analysis due to the lack of major element data.

Due to the nonlinear nature of the data, several transformations of the data were examined to find a suitable relationship. The logit transform:

$$\text{logit}(p) = \ln(p/(100-p)),$$

where p =percent removal and $\ln$ is the natural logarithm was selected. The logit is commonly used with fractions and percentage data to reduce the variance in the data and to simplify data analysis. Regression analysis performed on the logit values of the original data can be transformed back to the original data scale using the relationship:

$$p = 100(\exp(q)/(1+\exp(q))),$$

where $q = \text{logit}(p)$ and $\exp$ is the natural exponential function. A significant advantage of this procedure is that the equation will not yield removal values outside the range of 0-100 percent.

Regression analysis to determine the partitioning of trace elements was first performed on the transformed data to determine the relationship between trace element and ash removal using the equation:

$$\text{logit}(\text{ER}) = A + (B \times \text{logit}(\text{AR})),$$

where ER=percent element removal, AR=percent ash removal, and A and B are fitted regression coefficients. Regression analyses were also performed using total sulfur removal data:

$$\text{logit}(\text{ER}) = A + (C \times \text{logit}(\text{SR})),$$

where SR=percent total sulfur removal and C is a fitted regression coefficient. For selected elements, a joint relationship using both ash and total sulfur removal data was used to estimate element removal potentials:

$$\text{logit}(\text{ER}) = A + (B \times \text{logit}(\text{AR})) + (C \times \text{logit}(\text{SR})).$$

In a few cases, what appeared to be obvious outliers in the data set were not included in the development of the regression equations. Both visual observation of the data and the Cook's-d statistic were used to identify these apparent outliers.

4.1.3 Statistical Estimation of Partitioning Coefficients

Using the logit transformation described in Section 4.1.2, regressions were run on the data using element removal as the dependent variable and ash removal and sulfur removal as the independent variables. Ash and sulfur removal are parameters commonly obtained during standard coal washability tests and therefore are attractive as independent variables for predicting trace element partitioning. The strong statistical correlation of trace

element removal with ash removal and sulfur removal in the existing data also supports use of these two independent variables.

Table 52 presents the results of regressions obtained for trace element removal versus ash removal alone. Corresponding to the results obtained using simple linear correlation analysis, R^2 values for a number of elements are relatively good. Computer generated plots of the raw data and the fitted curves for aluminum and arsenic are presented in Figures 13 and 14, respectively. Fitted curves for all twenty elements are presented in Appendix III. As expected, the data for aluminum tightly fit about the predicted value line. The 95 percent confidence interval bands for the fitted value line and the individual points are relatively small. For arsenic, however, an element more closely associated with the sulfides in the coal than with the total ash content, the scatter of data and the width of the confidence intervals are large.

A plot of the arsenic removal data versus sulfur removal is presented in Figure 15. The fit of arsenic versus sulfur is better than for arsenic versus ash, but still shows more variability than present with aluminum versus ash. Plots for seven selected elements versus sulfur removal are in Appendix III.

For the elements which exhibited relatively strong correlations with sulfur removal as well as for selected other elements, fits of the element removal were made as a function of both ash and sulfur removal. These results are shown in Table 53. The R^2 values for lead, cobalt, arsenic, iron, selenium, and mercury are significantly improved. This result is to be expected given the mode of occurrence of these elements in association with pyrite (see Table 13). Also as expected, the R^2 for the chalcophiles cadmium, copper, and zinc—occurring as fine-grained sphalerite and chalcopyrite distributed throughout the coal matrix—is only slightly influenced by the addition of sulfur reduction as a variable. This also reflects the fact that although these three trace elements occur in coal as sulfides, only a small percentage of the total sulfur in the coal is present as trace element sulfides. The poor fit of cadmium relative to that of zinc—an element with which it is highly correlated—is not understood. The fitted family of curves for arsenic

TABLE 52. ESTIMATED TRACE ELEMENT REMOVAL DURING COAL WASHING BASED ON REGRESSION OF LOGIT TRANSFORM OF ASH REMOVAL DATA

Element	N	100% x R ²	Coefficients	
			Intercept ^a	% Ash Removed ^a
Al	33	95	-0.2107 (0.054)	1.0451 (0.042)
Si	31	94	0.2585 (0.056)	0.9285 (0.045)
V	33	91	-0.9691 (0.077)	1.1124 (0.063)
K	33	90	0.3398 (0.087)	1.1668 (0.068)
Na	34	86	-0.5754 (0.116)	1.3246 (0.092)
Ti	31	85	-0.0357 (0.089)	0.9040 (0.071)
Cr	43	84	-0.6115 (0.077)	1.0051 (0.069)
Be	33	75	-1.3232 (0.106)	0.8508 (0.087)
Pb ^b	43	74	-0.2583 (0.095)	0.9227 (0.085)
Mn	44	74	-0.0376 (0.150)	1.4249 (0.130)
Cu	42	70	-0.6770 (0.092)	0.7979 (0.082)
Co ^b	25	68	-0.8937 (0.168)	0.8703 (0.126)
Ni	42	67	-0.9964 (0.110)	0.8805 (0.097)
Zn	34	66	-0.0250 (0.145)	0.9127 (0.115)
P	33	56	-0.3041 (0.215)	1.0525 (0.169)
Ca	33	49	-0.4688 (0.227)	1.0123 (0.185)
Fe ^b	34	48	0.1355 (0.157)	0.6725 (0.124)
Se ^b	34	47	-0.6969 (0.133)	0.5590 (0.105)
As ^b	33	42	0.3095 (0.135)	0.4992 (0.105)
Hg ^b	44	38	-0.7126 (0.134)	0.5796 (0.115)
Cd	43	20	-0.0358 (0.183)	0.5024 (0.156)

N = The number of coal samples used in the regression.
R² x 100 = R-square expressed as a percentage. This is the percent of total variation around a horizontal (average) line that is reduced by tilting the line to the indicated regression line (R² is computed in the transformed scale).

^aCoefficients are for the logit equation (see Section 4.1.2); the standard error for each coefficient (a measure of the goodness of fit) is shown in parentheses.

^bElements showing significant improvement in R² when fit includes both ash and sulfur removal; see Table 54.

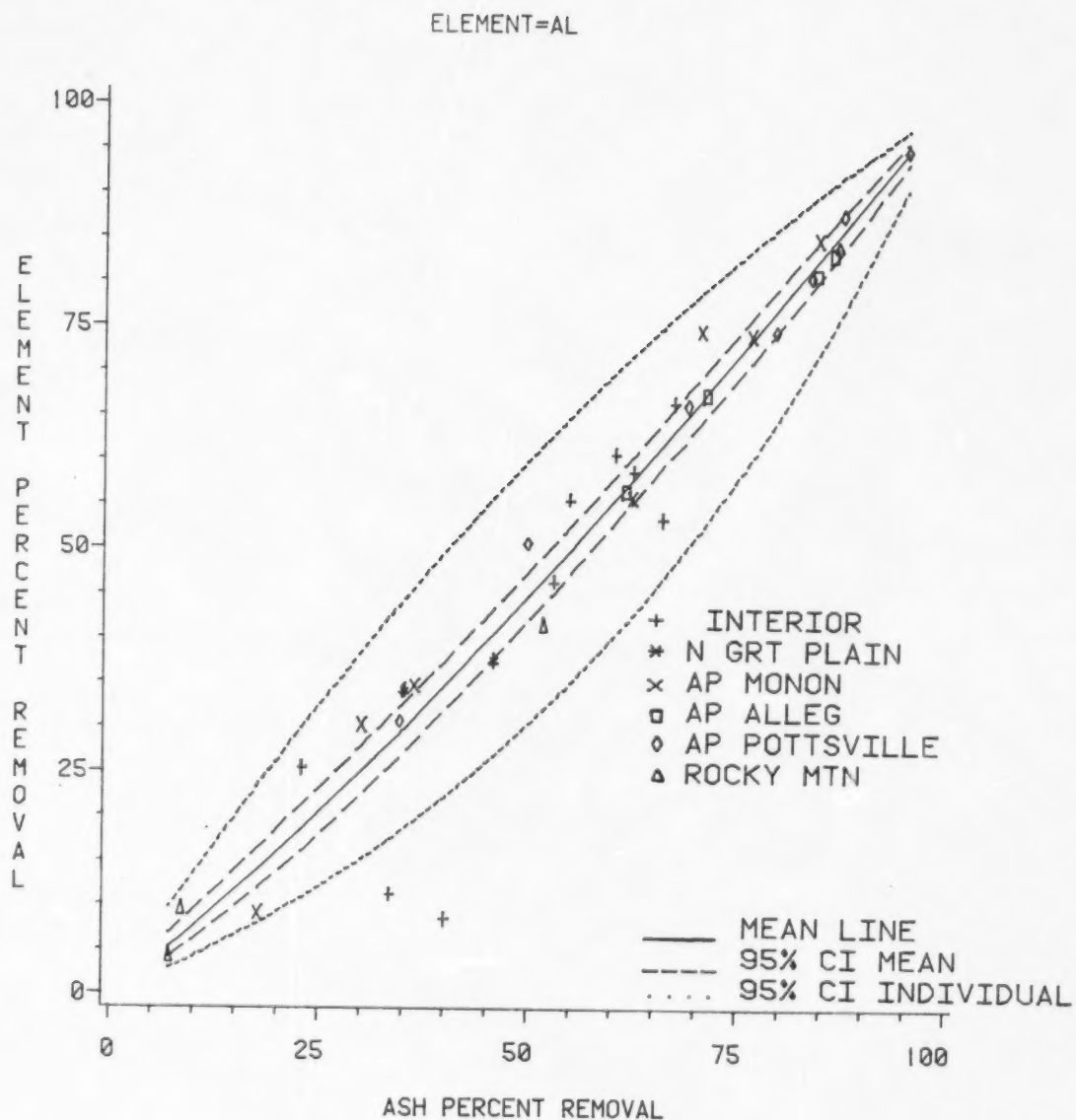


Figure 13. Regression Curve for Removal of Aluminum as a Function of Ash Removal

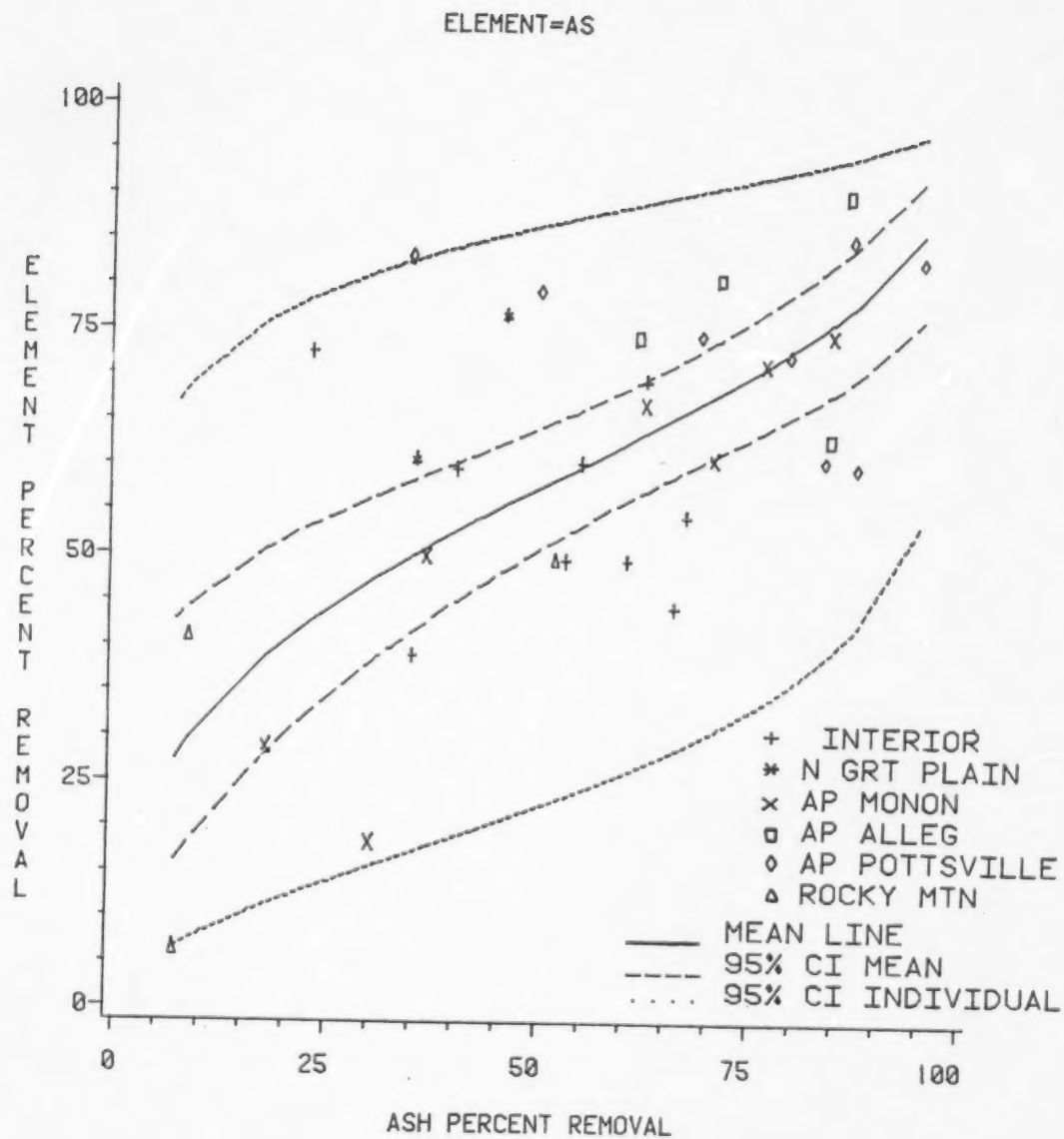


Figure 14. Regression Curve for Removal of Arsenic as a Function of Ash Removal

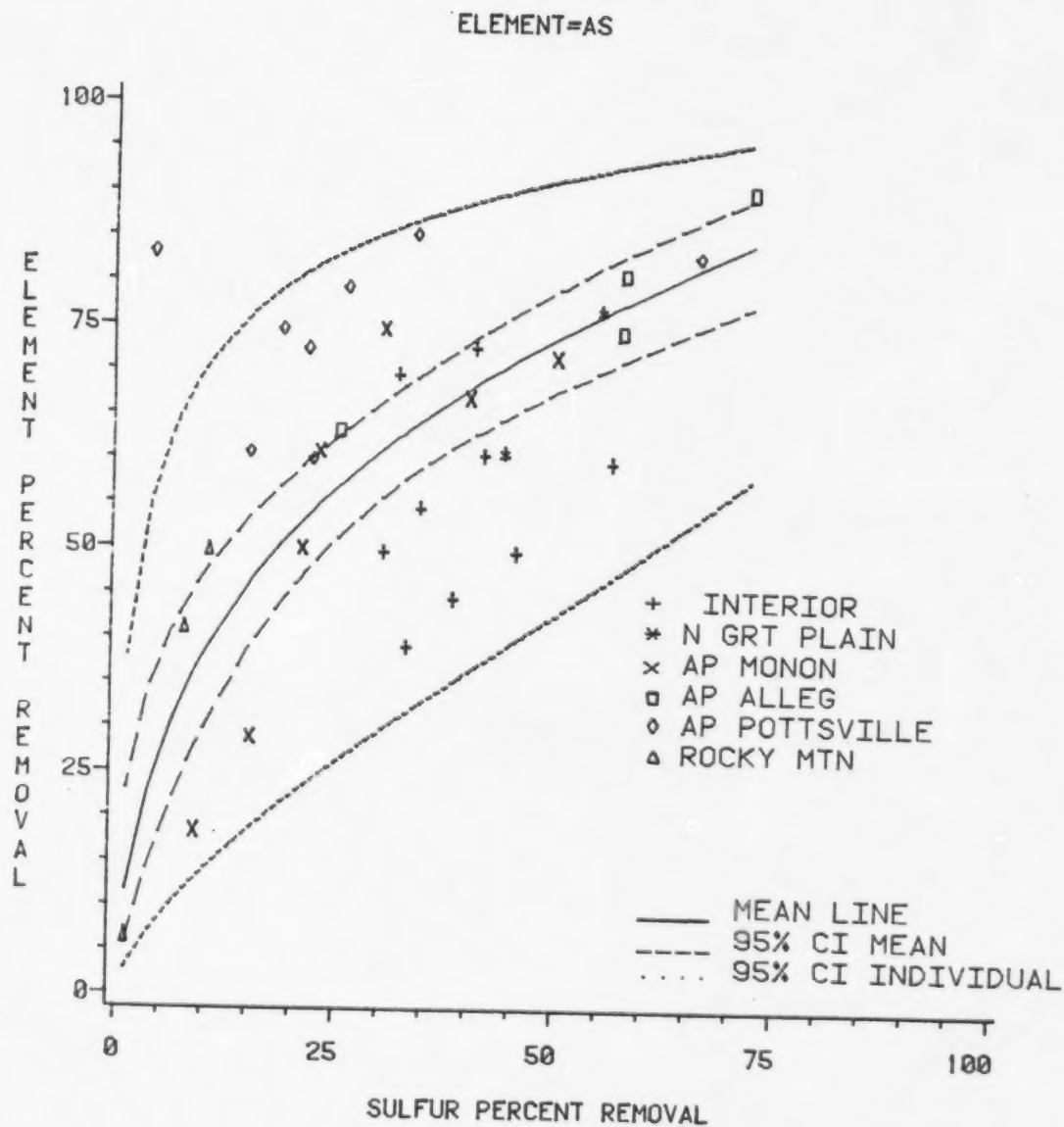


Figure 15. Regression Curve for Removal of Arsenic as a Function of Sulfur Removal

TABLE 53. ESTIMATED TRACE ELEMENT REMOVAL DURING COAL WASHING
BASED ON REGRESSION OF LOGIT TRANSFORM OF ASH AND
SULFUR REMOVAL DATA

Element	N	R ² x 100	Estimated Coefficients		
			a	b	c
Pb	43	74	-0.2583 (0.095)	0.9227 (0.085)	--
		51	0.7117 (0.166)	--	0.7978 (0.123)
		88	0.2024 (0.096)	0.7268 (0.067)	0.4615 (0.069)
Co	25	68	-0.8937 (0.168)	0.8703 (0.126)	--
		52	0.2525 (0.247)	--	0.8294 (0.166)
		79	-0.3696 (0.202)	0.6491 (0.120)	0.4615 (0.131)
As	33	42	0.3095 (0.135)	0.4992 (0.105)	--
		58	1.0303 (0.147)	--	0.6870 (0.107)
		70	0.7483 (0.147)	0.3145 (0.090)	0.4922 (0.107)
Fe	34	48	0.1355 (0.157)	0.6725 (0.124)	--
		53	1.0441 (0.187)	--	0.7810 (0.131)
		67	0.7004 (0.183)	0.4273 (0.115)	0.5444 (0.128)
Se	34	47	-0.6969 (0.133)	0.5590 (0.105)	--
		47	0.0280 (0.167)	--	0.6155 (0.116)
		63	-0.2741 (0.164)	0.3755 (0.103)	0.408 (0.115)
Hg	44	38	-0.7126 (0.134)	0.5796 (0.115)	--
		36	-0.0126 (0.175)	--	0.6192 (0.126)
		50	-0.2954 (0.179)	0.3958 (0.120)	0.4111 (0.130)
Cd	43	20	-0.0358 (0.183)	0.5024 (0.156)	--
		17	0.5608 (0.245)	--	0.5024 (0.175)
		25	0.2798 (0.273)	0.3633 (0.179)	0.2999 (0.196)
Cu	42	70	-0.6770 (0.092)	0.7979 (0.082)	--
		19	-0.0397 (0.196)	--	0.4826 (0.159)
		72	-0.5295 (0.129)	0.7477 (0.086)	0.1615 (0.102)
Zn	34	66	-0.0250 (0.145)	0.9127 (0.115)	--
		24	0.8042 (0.273)	--	0.6110 (0.191)
		67	0.1211 (0.211)	0.8493 (0.132)	0.1407 (0.147)

- N = The number of coal samples used in the regression.
R² x 100 = R-square expressed as a percentage. This is the percent of total variation around a horizontal (average) line that is reduced by tilting the line to the indicated regression line (R² is computed in the transformed scale).
a = The intercept coefficient (with its standard error in parentheses).
b = The ash removal coefficient (with its standard error in parentheses).
c = The sulfur removal coefficient (with its standard error in parentheses).

reduction as a function of both ash and sulfur reduction is plotted in Figure 16. The three dimensional nature of this fit makes it difficult to plot the actual data points and the confidence interval lines.

The effect of differences in analytical methods (specifically the top size to which the coal was ground) between ISGS, DOE, and BCR was examined to determine possible sources of variability or bias in the data. ISGS conducted its tests on coals sized to 3/8 inch x 20 mesh, DOE on 14 mesh x 0, and BCR on a composite of sizes ranging from 1-1/4 inch down to 20 mesh. Studies by Cavallero et al. (5) have indicated that size reduction is of importance in sulfur and ash removal (see Section 3.1). Review of the trace element data for the 44 coals examined in this study failed to show any strong dependency on top size. The absence of major element analyses for the 10 coals examined by DOE limited the ability to examine the effect of particle size on major elements—the major source of mineral matter in coal—to only two particle top sizes. Again, however, no clear variation in cleanability as function of top size was noticed.

Regional variations in the data were also considered. As indicated in Section 4.1.2, discriminant analysis using major elements was able to properly assign most of the 44 samples among the six groups used in the analysis, indicating that regional differences do exist. As shown in Figure 14 and 15, arsenic removal in the Pottsville Group is generally better than in the Interior Province for equal levels of ash and sulfur removal. Visual inspection of the plots in Appendix III indicates that these regional variations exist for other chalcophile elements (Cd, Fe, Hg, Ni, and Pb), but are generally absent for the lithophile elements. Also as with arsenic, coals from the Pottsville Group generally exhibit higher than average chalcophile removal levels while the Interior Province coals have below average removals for a given level of sulfur and ash removal. The Interior Province coals are also notable for the high level of variability in trace element removal relative to the fitted curves.

For most trace elements, visual inspection of the plotted data relative to the fitted curves indicates that the differences between coals from the

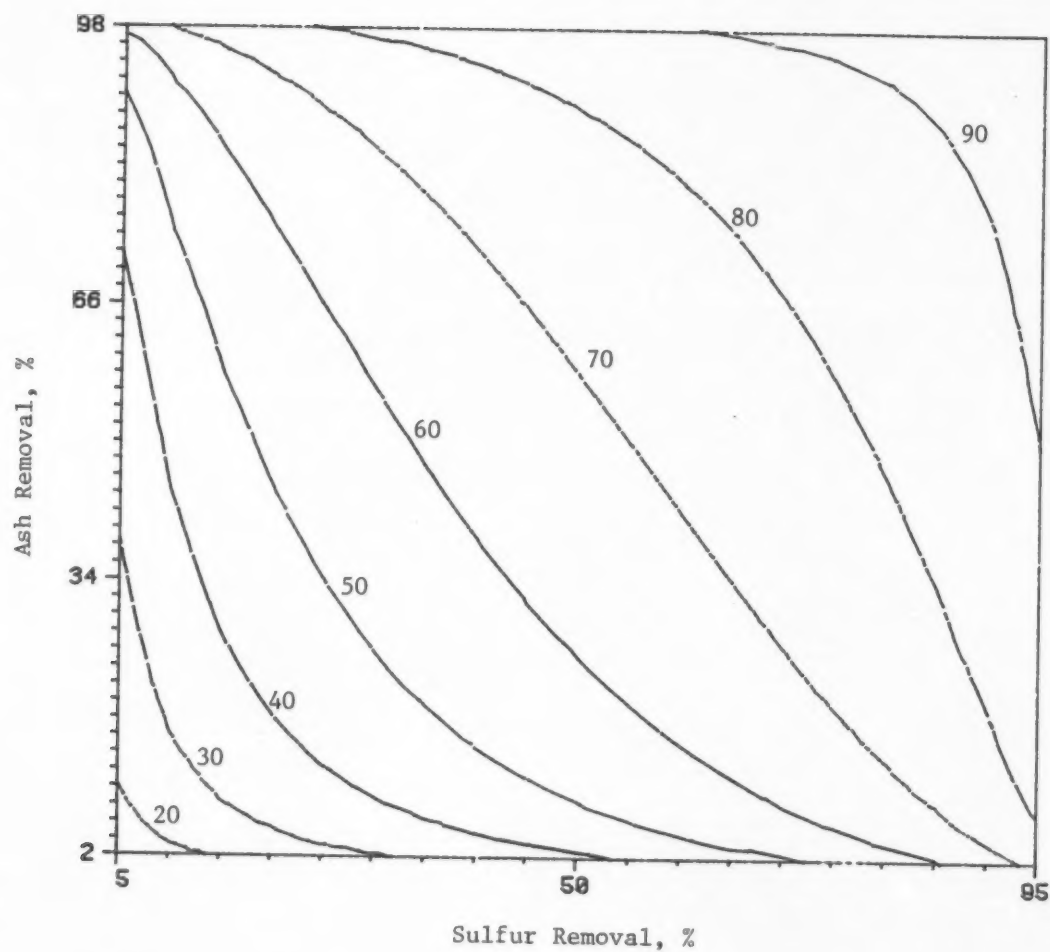


Figure 16. Regression Curve for Percent Removal of Arsenic as a Function of Percent Ash and Sulfur Removal

same group are frequently equal to or greater than the variability between groups. In these instances, similarities in removal values (e.g., the low values recorded for sulfur removal in the Rocky Mountain Province), rather than similarities in deviations from fitted values, are a major contributor to discriminant analysis performance. For these reasons as well as the limited number of data points within most of the regions, regression analysis of the data on a regional basis was not performed. Regional averages in trace element removal efficiencies versus sulfur and ash removal are plotted in Appendix IV; Figure 17 is an example plot for arsenic.

4.2 COAL COMBUSTION

4.2.1 Combustion Partitioning Data

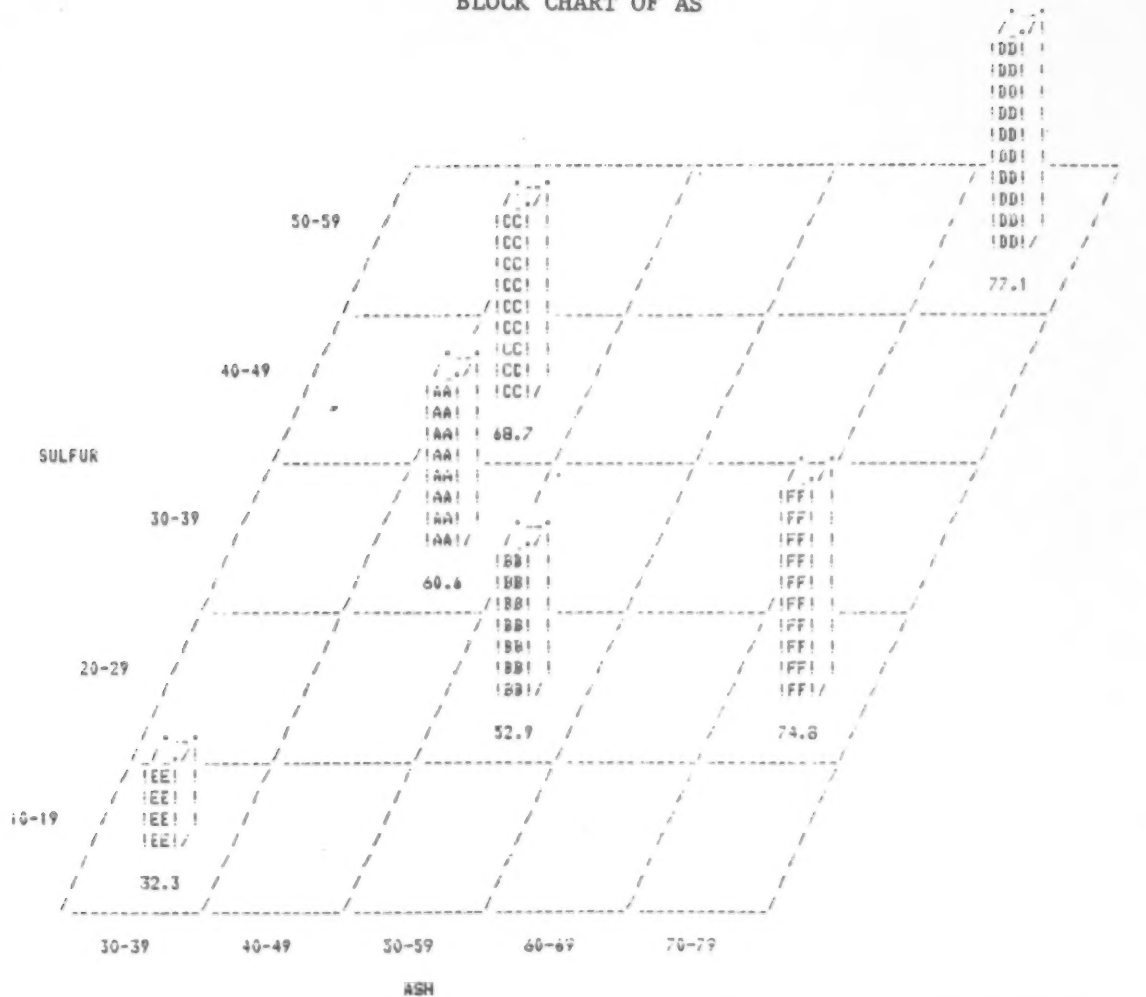
This section presents data from 15 studies (6-16) where a mass balance for each element and an overall closure were calculated:

$$\text{Closure} = \frac{\text{mass out} - \text{mass in}}{\text{mass in}} \times 100$$

The mass in was usually the elemental concentration in the coal times the mass flow of coal. Ideal closure, where all the mass of a particular element flowing into the boiler is accounted for by summing the mass flows of that element in the several output streams, would be 100%. Such a value indicates that the validity of the measurements is good; a closure of 50% or 150% would indicate that large errors were made in either sampling, analysis, or determining mass flows. A closure range of $\pm 30\%$ would still indicate reasonable data; outside this range, caution should be exercised in working with the data. Only studies with such closure calculations are considered, since it gives an indication of the quality of the data.

Table 54 presents the elemental distribution patterns for the more common major and trace elements. The column labeled emissions refers to the measurements of the flue gas/fly ash mixture exiting the plant via atmospheric (stack) emissions. All the plants included in the averages controlled particulate emissions with at least 98% control efficiency. Study No. 5, employing

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SYMBOL REGION

A = Interior
B = Ap-Alleg

C = N Grt Plains
D = Ap-Monon

E = Rocky Mtn
F = Ap-Pottsville

Figure 17. Regional Variations in Arsenic Removal Versus Sulfur and Ash Removals

TABLE 54. AVERAGE ELEMENTAL DISTRIBUTION OF FLY ASH

Element	No. of Points	Percent Distribution of Element ^a			Closure Percent
		Bottom Ash	Hopper Ash	Emissions	
Ag	3	5.4 ± 3.5	91.8 ± 5.2	2.8 ± 1.7	112 ± 4
Al	8	17.1 ± 5.4	81.6 ± 5.4	1.2 ± 1.6	96 ± 12
As	10	5.8 ± 8.0	84.4 ± 16.4	9.7 ± 14.0	114 ± 32
B	7	11.2 ± 8.8	81.3 ± 11.8	7.6 ± 9.5	106 ± 36
Ba	7	15.8 ± 5.0	82.8 ± 6.4	1.4 ± 3.0	128 ± 35
Be	9	15.3 ± 6.0	82.5 ± 8.6	2.2 ± 3.9	92 ± 22
Ca	6	17.8 ± 5.3	80.6 ± 5.2	1.6 ± 2.0	99 ± 16
Cd	7	9.1 ± 5.4	76.3 ± 20.9	14.6 ± 17.6	102 ± 34
Cl	4	6.9 ± 7.0	7.8 ± 7.4	85.3 ± 10.8	167 ± 140
Co	6	15.4 ± 3.7	82.3 ± 2.5	2.3 ± 1.6	98 ± 17
Cr	9	12.7 ± 5.2	80.5 ± 9.6	6.8 ± 8.8	121 ± 65
Cu	7	11.9 ± 3.2	83.4 ± 8.0	4.7 ± 7.3	83 ± 32
F	8	2.5 ± 2.6	60.2 ± 37.3	37.4 ± 38.2	73 ± 37
Fe	8	19.5 ± 4.9	79.3 ± 5.0	1.3 ± 1.5	115 ± 10
Hg	10	2.7 ± 3.9	31.3 ± 35.2	66.0 ± 38	62 ± 51
K	3	19.9 ± 1.2	79.1 ± 2.8	1.0 ± 1.7	104 ± 24
Mg	7	18.0 ± 4.3	79.9 ± 5.4	2.1 ± 2.4	103 ± 16
Mn	7	16.8 ± 6.1	80.8 ± 8.9	2.4 ± 4.4	122 ± 16
Mo	7	12.9 ± 14.9	63.9 ± 29.8	23.2 ± 34.0	141 ± 85
Na	3	15.5 ± 5.7	83.4 ± 3.9	1.1 ± 1.8	98 ± 23
Ni	9	14.4 ± 6.4	74.3 ± 13.9	11.2 ± 15.4	113 ± 32
Pb	10	7.0 ± 4.8	83.5 ± 18.0	9.5 ± 18.1	100 ± 60
S	5	3.1 ± 5.2	28.2 ± 36.4	68.6 ± 40.9	77 ± 50
Sb	8	7.1 ± 6.7	85.6 ± 13.9	7.3 ± 12.9	115 ± 83
Se	11	3.0 ± 3.9	71.1 ± 22.4	25.9 ± 22.1	64 ± 30
Ti	5	17.6 ± 5.6	81.2 ± 5.2	1.2 ± 1.3	92 ± 23
U	4	26.2 ± 16.0	71.8 ± 16.0	2.0 ± 1.9	65 ± 25
V	8	12.5 ± 6.5	83.8 ± 7.9	3.7 ± 3.5	100 ± 41
Zn	8	10.0 ± 8.7	85.1 ± 10.7	4.9 ± 5.4	127 ± 70

^aPercent distribution normalized to 100 percent by dividing measured values by closure value. Measured values equal normalized distribution times closure value.

a mechanical cyclone collector, was excluded from the averages because of high particulate emissions (over 50%) and because such technology is no longer in common use as the only form of particulate control. Data for silicon were found in only two studies; the average of those data showed 20.1% in the bottom ash, 79.9% in the hopper ash and none in the fly ash/flue gas emissions. Data for each plant are given in Appendix V.

The mass flow of the major ash-forming elements, which generally are not enriched or depleted in any waste stream, give an idea of the total mass partitioning. For example, for Al, Ca, Fe, Mg, and Ti, the percentage into the bottom ash averaged 18.0 ± 0.8 and the hopper ash averaged 80.5 ± 0.8 ; this would leave about 1.5% for the emissions. Using these values as indicative of total mass flow, one may quickly assess whether any other element is enriched or depleted in a particular output stream. Table 55 presents enrichment ratios with respect to aluminum, the element usually used to be indicative of the total mass. In Table 55, a value of 1.1 would imply a 10% enrichment of that element with respect to aluminum; the complete data table is given in Appendix V.

The bottom ash numbers and their standard deviations are generally consistent. Most elements are slightly depleted; the increased mass is taken up by silicon. Most hopper ash enrichment values are close to one (Table 55), indicative that most of the ash mass is hopper ash (about 80.5%). Due to the small fraction of mass in the fly ash/flue gas component and the difficulty in sampling and analysis of small samples, the emissions category shows great variability and large standard deviations. Some volatile elements show enrichments greater than 100 times aluminum, but the standard deviations are concomitantly large indicating large uncertainty overall.

Inspection of Tables 54 and 55 reveals the following details:

- Elements depleted in the bottom ash include Ag, As, Cd, Cl, F, Hg, Pb, S, Sb, Se and Zn. Only U appears to be enriched at all, and the standard deviation for U is large.

TABLE 55. AVERAGE ELEMENTAL ENRICHMENT IN ASHES WITH RESPECT TO ALUMINUM

Element	No. of Points	Enrichment of Element Relative to Al			Closure Percent
		Bottom Ash	Hopper Ash	Emissions	
Ag	3	0.18 ± 0.02	1.45 ± 0.45	9.75 ± 12.11	112 ± 4
Al	8	1.00 ± 0	1.00 ± 0	1.00 ± 0	96 ± 12
As	7	0.30 ± 0.36	1.09 ± 0.14	8.44 ± 12.28	114 ± 32
B	6	0.54 ± 0.37	1.04 ± 0.09	42.78 ± 64.62	106 ± 36
Ba	6	0.84 ± 0.16	1.04 ± 0.04	1.58 ± 1.55	128 ± 35
Be	6	0.86 ± 0.05	1.03 ± 0.01	1.61 ± 1.34	92 ± 22
Ca	5	1.00 ± 0.15	1.00 ± 0.03	1.82 ± 1.38	99 ± 16
Cd	4	0.39 ± 0.31	1.07 ± 0.06	18.58 ± 15.99	102 ± 34
Cl	4	0.34 ± 0.35	0.10 ± 0.09	428 ± 558	167 ± 140
Co	5	0.90 ± 0.20	1.02 ± 0.05	3.94 ± 4.33	98 ± 17
Cr	7	0.70 ± 0.17	1.02 ± 0.07	21.0 ± 10.7	121 ± 65
Cu	6	0.66 ± 0.08	1.05 ± 0.03	8.18 ± 12.17	83 ± 32
F	6	0.17 ± 0.17	0.92 ± 0.40	244 ± 455	73 ± 37
Fe	8	1.19 ± 0.23	0.97 ± 0.04	1.27 ± 0.62	115 ± 10
Hg	7	0.20 ± 0.24	0.42 ± 0.51	255 ± 282	62 ± 51
K	3	0.96 ± 0.10	1.01 ± 0.02	1.67 ± —	104 ± 24
Mg	6	0.95 ± 0.10	1.01 ± 0.02	2.13 ± 1.79	103 ± 16
Mn	6	1.03 ± 0.33	1.00 ± 0.06	1.48 ± 0.37	122 ± 16
Mo	6	0.78 ± 0.79	0.93 ± 0.26	47.7 ± 83.5	141 ± 85
Na	3	1.00 ± 0.03	1.00 ± 0.01	1.00 ± —	98 ± 23
Ni	7	0.85 ± 0.23	0.98 ± 0.07	24.9 ± 31.1	113 ± 32
Pb	7	0.42 ± 0.20	1.10 ± 0.10	5.66 ± 3.41	100 ± 60
S	5	0.16 ± 0.28	0.35 ± 0.45	412 ± 547	77 ± 50
Sb	7	0.40 ± 0.30	1.09 ± 0.10	6.18 ± 6.54	115 ± 83
Se	8	0.19 ± 0.25	0.90 ± 0.26	117 ± 239	64 ± 30
Ti	5	0.99 ± 0.16	1.01 ± 0.04	1.05 ± 0.16	92 ± 23
U	4	1.35 ± 0.97	0.92 ± 0.22	4.22 ± 3.29	65 ± 25
V	6	0.77 ± 0.24	1.04 ± 0.07	4.43 ± 3.79	100 ± 41
Zn	8	0.58 ± 0.41	1.04 ± 0.12	5.87 ± 3.24	127 ± 70

- Elements significantly depleted in the hopper ash are Cl, F, Hg, Mo, and S. Only Ag appears to be significantly enriched in the hopper ash.
- Those elements enriched in the fly ash/flue gas emissions are As, B, Cd, Cl, Cr, F, Hg, Mo, Ni, Pb, S, Sb, and Se.
- Note should be taken of the standard deviation of each number; a large deviation indicates a very broad range of values or that one data point was far from the average.
- Closure of from 70 to 130 percent is within the expected limits of sampling and analytical procedures. Values outside this range indicate that the partitioning data are uncertain. For example, Mo at 141 ± 85 implies a large uncertainty which is reflected in the standard deviation of each ash fraction.
- Low closure would tend to indicate some of the element was escaping detection in the waste streams (e.g., Hg, F). High closure indicates that either coal analysis was low or the waste stream samples are easily contaminated (e.g., Cl, Cr). Elements with poor closure (or large uncertainty) are Ba, Cl, Cr, Cu, F, Hg, Mo, Pb, S, Sb, Se, U, and Zn.

The values given in Table 54 may be taken as approximate emission factors for any similar type of pulverized coal boiler with a 98% particulate collection device (with the possible exception of a baghouse due to its more efficient collection of fine particles).

4.2.2 Statistical Analysis of Combustion Partitioning Data

Further analyses of these data were carried out, but the results are uncertain. For example, partitioning and enrichment were considered as a

function of coal rank; see Table 56. Less percentage mass was collected in the bituminous bottom ash than for the subbituminous bottom ash, but the enrichment factors with respect to aluminum were little different between the two ranks. Similar behavior was noted for most trace elements. The smaller percentage of bottom ash was probably due to boiler design and operation. While inconclusive due to the limited number of data points, it appears that certain elements, particularly the chalcophiles (As, Fe, Pb, Zn), are enriched in the emissions stream of subbituminous coals. Again, however, general conclusions are potentially erroneous given the limited number of data points.

TABLE 56. DISTRIBUTION OF SELECTED MAJOR AND TRACE ELEMENTS BY COAL RANK FOR PULVERIZED COAL COMBUSTION

Element	Number ^b		Bottom Ash ^b		Hopper Ash ^b		Emissions ^b	
	B ^a	SB ^b	B ^a	SB ^b	B ^a	SB ^b	B ^a	SB ^b
Al	1	6	9.0	19.8	89.3	79.1	1.7	1.1
As	3	7	2.0	7.4	90.9	81.7	7.1	10.9
Be	2	7	5.5	18.1	94.6	79.1	0	2.8
Ca	1	5	8.3	19.7	88.8	79.0	2.9	1.3
Cr	2	7	7.8	14.1	88.8	78.1	3.4	7.7
Fe	2	6	13.1	21.6	85.7	77.2	1.2	1.3
Mg	1	6	9.6	19.4	87.0	78.7	3.4	1.9
Pb	3	7	4.2	8.2	91.6	80.1	4.1	11.8
S	1	4	0.0	3.9	2.1	34.7	97.9	61.3
Ti	1	4	9.5	19.6	87.4	79.7	3.1	0.8
V	1	7	8.5	13.0	86.2	83.5	5.3	3.5
Zn	2	6	5.6	11.4	89.0	83.9	5.5	4.7

^aB=bituminous coal (from Studies 8, 10, 12 in Appendix V)

^bSB=subbituminous coal (Studies 3, 4, 6, 7, 11, 13, 14, 15 in Appendix V)

In an effort to identify possible elemental relationships of importance, a correlation matrix was calculated (i.e., linear regression correlations) for all emission and enrichment factors versus coal concentrations for all elements. Several hundred statistically significant correlations resulted; a correlation was deemed significant if the correlation factor was 0.95 or greater and the p-value was less than 0.05. Further inspection indicated that most of the high correlations were due to a data distribution patterns composed of a fairly tight cluster of data points and one outlying point. High

correlations in this type of pattern do not represent any kind of verifiable trend, but rather reflect the statistical uncertainty of sparse and unevenly spaced data. In some cases, a rather well defined straight line was present, but generally there was no identifiable chemical basis for the trend. By way of example, no strong correlations were found for coal concentrations of Al, Ca, K, Mg, Na, Ti; a few were present with Fe (e.g., in hopper ash Na, K, Cd, Ca, Co and S correlated, K and S were negative while the rest were positive). Since the number of data points was seldom more than eight, it is felt that the quality and quantity of data were insufficient to justify the identification of trends.

A more sophisticated regression (rank weighted analysis) program was used in order to reduce the influence of an outlying point. This method assigns each point an equal weight in determining correlation coefficients for the data. A large number of correlations were obtained again. However, for cases where a strong correlation might be expected based on expected chemical reactions (e.g., sulfur in the hopper ash correlating with Na or Ca in the coal), none were found.

It is even more difficult to assess the importance of mineral forms in the coal on the distribution of elements in the combustion ashes. No study was found that reported elemental data in the coal and ash along with mineral forms in the coal. It is generally believed that the mineral forms in the coal have little influence on the fate of the elements in large pulverized coal boilers; several authors even stated as much (17, 18). For stoker boilers, where the maximum temperature is substantially lower, some mineral forms may remain intact during the slower combustion. However, no study was found reporting mineral forms in stoker-fired ashes.

Because of these shortcomings, further efforts to investigate the relationship between sulfur and trace element partitioning versus various coal properties were not made. The existing evidence, while sparse, tends to suggest that partitioning of the elements is largely independent of the properties of the coal. Current thought is that the process of elemental partitioning during combustion is determined by the process conditions (e.g.,

temperature and combustor design), but again data is insufficient to detail these relationships in any well-defined manner. Therefore, the data presented in Tables 54 and 55, while exhibiting substantial variability due to both analytical imprecision and differences in the processes and coals tested, provide the best current estimates of trace element partitioning during coal combustion.

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SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

Over the past decade, significant research has been conducted on the occurrence of sulfur and trace elements in coal and the impacts of their release into the environment. As a result, analytical data are now available on the abundance of sulfur and trace elements in coals from most regions of the U.S. and for the partitioning of these elements for selected coals in selected processes. The limitations of the data are large, however.

Those familiar with coal caution strongly against making generalizations. Nevertheless, generalizations are useful in that they provide a reference point for further discussion and a basis for building a better understanding. In this spirit, the following conclusions and recommendations are provided.

5.1 CONCLUSIONS

5.1.1 Coal Quality

Efforts to evaluate sulfur and trace elements in coal can be divided into two major groups: one group being purely descriptive and the other attempting to be explanatory. In the first group are the analyses of numerous coals from throughout the various regions of the U.S. The second group consists of the efforts of various coal geologist and geochemists to develop a conceptual understanding of the processes by which sulfur and trace elements were deposited and occur in coal. Based on these studies, predictive models can then be developed.

Sources of descriptive information on sulfur and trace elements in coal are available from several places. The major source of such information within the federal government is the U.S. Geological Survey. To date the USGS has evaluated and reported trace element concentrations in over 4,400 coal samples from throughout the U.S. This number is dwarfed by the enormity of the U.S.

coal resource base, however. Relative to the identified coal resource base, these 4,400 plus samples represent roughly one sample per 400 million tons of coal (U.S. coal production in 1981 was 824 million tons). Broken down by rank, the tonnage of identified resource per sample ranges from roughly 200 million tons for bituminous coal, to 750 million tons for subbituminous coal, and 2.6 billion tons for lignite. Substantially less information has been catalogued on the modes by which trace elements occur in coal, the mineralogy of the major ash-forming elements, or the petrology of the organic matter. Without this information, assessment of the environmental advantages and disadvantages of various coal use technologies, especially coal cleaning, is limited.

In order to better understand how trace elements are likely to occur in coals and to avoid the extremely large cost associated with gathering and analysis of numerous additional samples, coal scientists have increasingly sought to develop models for predicting coal quality based on the depositional environmental and geochemistry of coal-forming systems. The major analytical methods used for this work include gravity separation studies, microscopic observation, and sophisticated chemical analyses. The interpretation of these data, and thus the development of the resulting models, have substantially differed. Specific disagreements on the interpretation of existing data relative to the modes of trace element occurrence include the relative importance of detrital materials on the total mineral content in coals, the extent and nature of chemical bonding between the organic structure of coal and various trace elements, and the significance of carbonate materials versus post-depositional marine influences on the level of sulfur and chalcophile trace elements.

At present, the major constraints to better understanding the significance of sulfur and trace elements relative to environmental control technology needs are 1) disagreement among coal scientists on the methods of analysis and the interpretation of results relative to the modes of occurrence and origin of trace elements in individual coal samples, and 2) the lack of a detailed framework for predicting the modes of sulfur and trace element occurrence for a seam or region based on existing samples and associated geologic,

geochemical, and other paleoenvironmental data. Given these constraints, the priority research needs relative to the coal resource itself appear to be in the interpretation of existing data and the development of a conceptual framework for interpreting these data on a seam and/or regional basis. Given the magnitude of the U.S. coal resource base combined with the extent and variability of existing data, collection and analysis of further samples (except as relate to the permitting and evaluation of new mines and coal-using facilities) will provide little additional information.

Despite these constraints, however, there is substantial agreement in many important areas. Specifically, general variations in sulfur and trace element composition as a function of rank and regional location have been established (see Tables 7-9), and the modes of occurrence for most elements have been defined (see Table 13). Also, the conceptual design of several models for explaining the origin and mode of occurrence in coals have been proposed (see Section 2.4).

5.1.2 Preparation

The effect of coal quality on coal processing and utilization technologies is most direct in the area of coal cleaning. Due to absence of high-temperature thermal processes during coal cleaning, the maceral and mineral forms in the coal are unaltered by the cleaning process. The importance of the mode of occurrence for sulfur and trace elements has been well demonstrated. Pyritic sulfur and trace elements (specifically As and Hg) associated with pyrite and trace elements associated with the extraneous clay minerals can be removed from as-mined coal with relatively high efficiency. Other trace elements which are associated with fine-grained minerals intimately mixed with the organic matrix or which are chemically bonded to the organic matrix are generally not removed during conventional cleaning. Variability in coal cleanability between regions and seams can be partially explained by the mode in which various elements occur, but the geologic and geochemical processes responsible for these variations between coals is poorly understood.

Based on available (and in most cases, limited) data, it appears that the removal of most of the common trace elements can be reasonably correlated with the removal of ash and sulfur from the coal as determined from standard washability tests. Little correlation exists between the amount of a trace element in a coal and its removal efficiency. For most of the chalcophile elements, the removal of total sulfur is a better estimator of trace element removal potential than is the removal of pyritic sulfur. As with sulfur removal, the removal of chalcophile trace elements for Allegheny Formation coals are generally higher than for other U.S. coals having similar ash and sulfur removal potentials. Coals from the Interior Province exhibit significant variations in cleanability. Partitioning coefficients as a function of six of the major coal-producing regions and as a function of the ash and sulfur removal potential are presented in Section 4.1.

5.1.3 Combustion

Most of the evidence to date and conventional thought suggests that the coal combustion process is the dominant factor in the partitioning of trace elements during combustion and that the modes of occurrence of various minerals and elements are not significant. The major determinants of the actual amounts of ash and individual elements partitioning into various processes streams are thus primarily a function of the boiler and environmental control systems design and of the absolute amount of each element in the as-fired coal. In the high temperatures of the combustion zone (with the possible exception of lower-temperature stoker boilers), the original mineral forms and modes of occurrence of individual elements appear to be completely destroyed.

The availability of data from commercial-scale coal-burning facilities for which material balances have been conducted to examine the quality of the data is limited. As such, determining the impact of subtle differences in partitioning as a function of various coal properties is not possible with statistical confidence. Partitioning factors between boiler ash, hopper ash, and stack emissions as a function of the mass of each element and as a function of the total mass flow of ash are presented in Tables 54 and 56,

respectively. Based on limited data, some evidence suggests that there may be some effect of coal rank on partitioning coefficients, particularly for the chalcophile elements.

Due to the volatility of certain elements and enrichment on the surface of small particles, high levels (greater than 10 percent) of the total mass of some elements (Cd, Cl, F, Hg, Mo, Ni, and Se) may be emitted to the atmosphere. Significant amounts of As, B, Cr, Pb, and Sb may also be emitted. However, to date no adverse environmental impacts from these emissions have been demonstrated. Correlations between the level of an element in the coal and the partitioning of other elements (e.g., the effect of Ca in the coal on the percentage of S in the hopper ash) were examined during the study, but were not statistically significant.

5.1.4 Synfuels

Studies of the effects of sulfur and trace elements on synthetic fuels processes have primarily focused on the catalytic effects of various elements on synfuels processes and the partitioning of these elements in various process and waste streams. With one exception, this study found no data which could be used to determine the impact of coal properties on the partitioning or ultimate environmental fate of sulfur and trace elements during conversion. As such, data are insufficient to support the correlation of coal properties with the environmental significance of synfuels processes.

5.1.5 Leaching

Other than air emissions, probably the greatest potential impact from coal utilization is from the leaching of solid wastes. The impact of coal properties from coal cleaning wastes have been identified; of particular concern is the high level of pyrites and other acid-forming minerals. Based on existing data, it appears that environmental impacts from disposal of these wastes can be controlled by controlling the acidity of the waste and the proper design of the waste disposal site. The relationship between the original properties of the coal and the leachability of trace elements from combustion

wastes are largely unknown, except as relates to the total quantity of an element in the coal. While some correlation can be made between the major ash-forming elements and leachate characteristics, direct correlations based on trace elements are not yet possible. This is understandable given the large number of variables effecting leachability. Substantial errors also exist between leachate results obtained using laboratory leaching methods versus those obtained under actual field conditions.

5.2 RECOMMENDATIONS

5.2.1 Coal Quality

- Extension of Depositional Models to Include Coal Quality. Depositional models have been developed to interpret the relationship between ancient peat-forming environments and coal deposit geometry. These models can aid coal geologists in interpreting the lateral continuity, thickness, and overall tonnages in a seam; and the association of coals with other sedimentary facies. Correlations have also been made between depositional environments and the ash and sulfur contents of coals. The next logical step is the extension of these models to help predict additional coal quality information based on depositional chemistry and other relevant parameters. The existing work of the USGS and other coal scientists discussed in Section 2.4 could serve as a basis for this work.
- Additional Study of the Origin of Mineral Matter in Coal. As indicated in Section 2.4, significant disagreements still exist among coal geoscientists over the relative importance and origin of various minerals in coal. Currently two significantly different models exist. One of the models assumes that detrital materials account for a significant portion of the mineral matter in most coals. The other model assumes that detrital minerals are of minor importance. Using existing

analytical methods, support for both models has been demonstrated using the same coal samples. Refinement of these models and reevaluation of existing data need to be made in order to reconcile these differences. Where appropriate, additional analytical procedures and coal samples should also be examined.

- **Factors Influencing the Distribution of Mineral Matter in Coal.** Directly related to the above recommendations is the analysis of depositional factors which influence the extraneous versus inherent nature of ash found in coal. Extraneous ashes can be readily removed from coals by conventional washing techniques while inherent ash cannot be removed. As discussed in Section 3.1, coals such as those from the Allegheny Formation have good washability while those from the Monongahela are more difficult to clean. Determination of the major difference in the coals as a function of mineralogy, depositional environments, and other related factors could be beneficial in evaluating the use of future coal resources.
- **Additional Analysis of the Mode of Trace Element Occurrence.** Existing trace element data bases, such as the USCHEM file currently maintained by the USGS are focused on providing information on the quantity of trace elements in U.S. coals, but do not provide information on the modes of occurrence for these elements. Before extensive data compilations on mineralogy or other characteristics are made, however, development of standardized procedures for evaluating samples is needed. Existing methods are both expensive and imprecise.

5.2.2 Coal Utilization

- **Trace Element Washability for Additional Coals.** The 44 coals included in this study include samples from the major

coal provinces in the U.S., but provide little or no information on a number of the major coal-producing seams and regions in the U.S. By comparison, sulfur removal data is available for over 750 samples. Specific attention in the additional studies should be given to major coal seams and regions which are presently washing coals or for which coal washing is likely in the future.

- **Impact on Mineralogy on Cleanability.** During this study the potential for trace element removal from coals was examined relative to the major ash-forming elements and as a function of the level of ash and sulfur removable from the coal. Neither of these approaches directly evaluate the minerals in the coals. Studies similar to those discussed in Sections 3.1 and 4.1 should be done, but including analysis of the minerals in the coals and the modes of occurrence for the trace elements.
- **Additional Analysis of Existing Data on Partitioning During Combustion.** The current study limited analysis of the partitioning of trace elements during combustion to studies for which material balances were also accomplished. A significant number of additional studies (estimated at 30-50) have been completed which give elemental concentrations in various combustion waste streams without measuring flow rates. While estimation of absolute elemental distributions between process streams are not possible for these studies, it is possible to estimate enrichment ratios. Using these studies, the data base on partitioning of trace elements during combustions could be significantly expanded. Such a data base should be large enough to allow a more detailed analysis of statistical relationships associated with combustion partitioning.
- **Catalytic Effects of Trace Elements on Sulfur Retention.** Vanadium, iron, and certain other elements have the potential for serving as a catalyst for the conversion of SO_2 to SO_3 .

Because of the increased efficiency by which SO_2 is absorbed onto the surface of fly ash particles, this catalytic effect may be important, but has not been extensively investigated.

- **Correlation of Leaching Characteristics with Coal Properties.** Little research has been done to date on the effects of coal properties on the composition of combustion ashes and their associated leachabilities. As discussed in Sections 3.2 and 3.4, the leaching potential of fly ash is related to the abundance and composition of spinel (ferrite oxide) versus aluminosilicates in the ash which in turn is believed to be associated with the composition of the coal. However, these relationships have not been well defined. Taking samples of coal and coal ash collected in the same time periods and under well known operating conditions, detailed analyses of the coal and leachability of the ash should be made and correlations between analyses examined.

APPENDIX I
SULFUR AND TRACE ELEMENT DATA BASES

Appendix I
SULFUR AND TRACE ELEMENT DATA BASES

Analytical data on sulfur and trace elements in coal are available in two major data bases developed by the USGS and Pennsylvania State University. Additional data have also been developed by state geological surveys, universities, and private organizations, but with the exception of information submitted to USGS for inclusion in their data base, they are not generally available in a format readily accessible for large-scale data analysis. The most significant source of data on trace elements and sulfur which is not currently accessible via computerized data base is the data compiled by the Illinois State Geological Survey. An agreement between ISGS and USGS for transfer of these data to USGS is in place but the actual transfer has not yet been accomplished. The following two sections review the contents of the USGS and Penn State data systems.

USGS National Coal Resources Data System (NCRDS)

The NCRDS data base is the most comprehensive source of geologic information on U.S. coal resources available. As of June 1981 NCRDS consists of 13 major data files, six of which are available for public use with the remainder still under development. Each of these major files and subfiles is identified and briefly described in Table I-1. More information on these files is available from USGS (1).

Geochemical and trace element data within NCRDS is stored on the file USCHEM. The file provides storage locations for 128 separate coal parameters and, as of October 1982, contains 7,533 sample analyses. Data cover all U.S. coal provinces. The 128 parameters used for describing each sample and the analytical methods used for coal analysis are presented in Tables I-2 and I-3, respectively.

TABLE I-1. NCRDS MAJOR FILES AND SUBFILES (as of June 1981)

Major File	Subfile	Type ¹	Description
USCOAL			Divided into three subfiles
	ECOAL	A	Tonnage data on Eastern U.S. coal resources by seam and county
	WCOAL	A	Tonnage data on Western U.S. coal resources by seam and county
	NEWCOAL	A	Recent tonnage data on all U.S. coal resources (includes possible data overlap with ECOAL and WCOAL)
BMALYT		A	Proximate, ultimate, Btu, and ash fusion temperature from U.S. Bureau of Mines files
BMRESBAS		A	Summary of tonnages and analysis by county
USTRIP ²		A	Summary of strippable coal resources
USTRAT ²		P	Stratigraphic data, subdivided into the following state subfiles: MTSTRAT, WYSTRAT, COSTRAT, VASTRAT, WVSTRAT, ALSTRAT, NMSTRAT, KSSTRAT, KYSTRAT, PASTRAT, MDSTRAT, TNSTRAT, MOSTRAT, ARSTRAT, MSSTRAT; plus CROSTRAT containing map data of the USGS Conservation Division
USGEOL ²		P	Geologic data by field
USALYT		P	Proximate, ultimate, Btu, forms of sulfur, rank, swelling index, and grindability
USCHEM		P	Proximate, ultimate, Btu, forms of sulfur, rank, swelling index, major ash oxides, and trace elements
USPET		P	Petrographic analysis data
USMIN ²		P	Mineralogical analysis data

(Continued)

TABLE I-1. NCRDS MAJOR FILES AND SUBFILES (as of June 1981) (Continued)

Major File	Subfile	Type ¹	Description
USPEAT ²		P	Peat data
USTOPO ²		P	Topographic data
USTEST ²		P	Rank, grindability, coke type, hardness, plastometer, and washability data

¹A = Areal data (e.g., by county); P = Point data (e.g., for individual samples)

²Files not available for use as of June 1981.

Source: Reference 1.

Other NCRDS data bases of importance for characterization of coal quality are USALYT which contains rank, proximate, ultimate, sulfur forms, swelling index, grindability, and ash fusion analyses, and USPET which contains petrographic data. Analytical procedures used for analysis of samples in these two files as well as USCHEM are carefully specified so as to minimize data problems associated with poor analytical quality.

A fourth file in NCRDS containing coal quality data is BMALYT. This file contains data similar in scope to USALYT. However, samples in this file have been obtained for many years and from a variety of public and private organizations. USGS does not exercise control over analytical procedures used on data contained in this file and, as such, variations in quality may be due to differences in analytical precision as well as actual differences in coal composition.

Penn State Coal Data Bank

The Penn State Coal Data Bank is oriented toward detailed description of selected coal samples (2). The data base provides for the storage of 370 separate characteristics for each sample and has the capability to compute 225

TABLE I-2. NCRDS USCHEM DATA ITEMS

1. STATE	45. CARBON	88. Hf* - Hafnium
2. COUNTY	46. OXYGEN	89. Hg* - Mercury
3. LATITUDE	47. HYDROGEN	90. Ho* - Holmium
4. NS	48. NITROGEN	91. In* - Indium
5. LONGITUDE	49. SULFUR	92. Ir* - Iridium
6. EW	50. SULFATE	93. La* - Lanthanum
7. AAPG PROVINCE	51. SULFUR-PYRITIC	94. Li* - Lithium
8. COAL PROVINCE	52. SULFUR-ORGANIC	95. Lu* - Lutetium
9. REGION	53. AIR DRIED LOSS	96. Mn* - Manganese
10. FIELD	54. USGSASH (525°C)	97. Mo* - Molybdenum
11. DISTRICT	55. SiO2*	98. Nb* - Niobium
12. FORMATION	56. Al2O3*	99. Nd* - Neodymium
13. GROUP	57. CaO*	100. Ni* - Nickel
14. BED	58. MgO*	101. Os* - Osmium
15. MEMBER	59. Na2O*	102. Pt* - Lead
16. ZONE	60. K2O*	103. Pd* - Palladium
17. DEPTH	61. Fe2O3*	104. Pr* - Praseodymium
18. SAMPLE THICKNESS	62. MnO*	105. Pt* - Platinum
19. SYSTEM	63. TiO2*	106. Rb* - Rubidium
20. SERIES	64. P2O5*	107. Re* - Rhenium
21. LOCATION NAME	65. SO3*	108. Rh* - Rhodium
22. QUADRANGLE	66. Ag* - Silver	109. Ru* - Ruthenium
23. COLLECTOR	67. As* - Arsenic	110. Sb* - Antimony
24. FIELD ID NO.	68. Au* - Gold	111. Sc* - Scandium
25. DATE	69. B* - Boron	112. Se* - Selenium
26. ESTIMATED RANK	70. Ba* - Barium	113. Sm* - Samarium
27. MAJOR RANK CAT.	71. Be* - Beryllium	114. Sn* - Tin
28. MINOR RANK CAT.	72. Bi* - Bismuth	115. Sr* - Strontium
29. ALPHA ID	73. Br* - Bromine	116. Ta* - Tantalum
30. NUMERIC ID	74. Cd* - Cadmium	117. Tb* - Terbium
31. LABCODE	75. Ca* - Cerium	118. Te* - Tellurium
32. SAMPLE TYPE	76. Cl* - Chlorine	119. Th* - Thorium
33. ANALYSIS TYPE	77. Co* - Cobalt	120. Tl* - Thallium
34. VALUES REPRESENT	78. Cr* - Chromium	121. Ts* - Thulium
35. OTHER TESTS	79. Cs* - Cesium	122. U* - Uranium
36. STU	80. Cu* - Copper	123. V* - Vanadium
37. ASH DEFORMATION	81. Dy* - Dysprosium	124. W* - Tungsten
38. ASH SOFTENING	82. Er* - Erbium	125. Y* - Yttrium
39. ASH FLUIDIZATION	83. Eu* - Europium	126. Y* - Ytterbium
40. FREE SWELLING	84. F* - Fluorine	127. Zn* - Zinc
41. MOISTURE	85. Ga* - Gallium	128. Zr* - Zirconium
42. VOLATILE MATTER	86. Gd* - Gadolinium	
43. FIXED CARBON	87. Ge* - Germanium	
44. BMASH (750°C)		

*These items will also have a code to identify detection qualifiers.

Source: Reference 1

TABLE I-3.

Category: geochemical data (ash, oxides)

name	type	description
a1a2	S	a1a2 value in per cent in ash (spec, arfrarf)
a1a3	S	a1a3 value in per cent in ash (spec, arfrarf)
cgo	S	cgo value in per cent in ash (spec, arfrarf)
eao	S	eao value in per cent in ash (spec, arfrarf)
n2o	S	n2o value in per cent in ash (spec, arfrarf)
k2o	S	k2o value in per cent in ash (spec, arfrarf)
fz2a3	S	fz2a3 value in per cent in ash (spec, arfrarf)
seo	S	seo value in per cent in ash (spec, arfrarf)
tio2	S	tio2 value in per cent in ash (spec, arfrarf)
p2a3	S	p2a3 value in per cent in ash (spec, arfrarf)
so3	S	so3 value in per cent in ash (spec, arfrarf)

Category: geochemical data (ba - fr)

name	type	description
ag	S	ag value in ppm - ash (spec, spec)
as	S	as value in ppm - whole coal (anaa, uetchem)
au	S	au value in ppm - ash (spec, spec)
b	S	b value in ppm - ash (spec, spec)
ba	S	ba value in ppm - ash (spec, spec)
be	S	be value in ppm - ash (spec, spec)
bl	S	bl value in ppm - ash (spec, spec)
br	S	br value in ppm - ash (ana)
cd	S	cd value in ppm - ash (uetchem, uetchem)
ce	S	ce value in ppm - ash, uc (spec, ana-750527/spec)
cl	S	cl value in ppm - whole coal (arfrarf)
co	S	co value in ppm - ash, uc (spec, ana-750527/spec, ana-740819)
cr	S	cr value in ppm - ash, uc (spec, ana-750527/spec, ana-740819)
cu	S	cu value in ppm - ash, uc (spec, ana-750527/spec)
cy	S	cy value in ppm - ash (uetchem, uetchem)
d	S	d value in ppm - ash (spec, spec)
er	S	er value in ppm - ash (spec, spec)
f	S	f value in ppm - ash, uc (spec, ana-750527/spec)
g	S	g value in ppm - whole coal (uetchem, uetchem)
ga	S	ga value in ppm - ash (spec, spec)
gd	S	gd value in ppm - ash (spec, spec)
ge	S	ge value in ppm - ash (spec, spec)
hf	S	hf value in ppm - ash, uc (spec, ana-750527/spec)
hg	S	hg value in ppm - whole coal (uetchem, uetchem)
ho	S	ho value in ppm - ash (spec, spec)
i	S	i value in ppm - ash (spec, spec)
ir	S	ir value in ppm - ash (spec, spec)

Category: geochemical data (la - zr)

name	type	description
la	S	la value in ppm - ash (spec, ana-750527/spec)
lu	S	lu value in ppm - ash (uetchem, uetchem)
ll	S	ll value in ppm - ash, uc (spec, ana-750527/spec)
na	S	na value in ppm - ash (spec, uetchem, spec, uetchem)
nb	S	nb value in ppm - ash (spec, spec)
nd	S	nd value in ppm - ash (spec, spec)
ni	S	ni value in ppm - ash (spec, spec)
ns	S	ns value in ppm - ash (spec, spec)
pb	S	pb value in ppm - ash (uetchem, uetchem)
pd	S	pd value in ppm - ash (spec, spec)
pr	S	pr value in ppm - ash (spec, spec)
pt	S	pt value in ppm - ash (spec, spec)
rb	S	rb value in ppm - ash, uc (spec, ana-750527/spec)
re	S	re value in ppm - ash (spec, spec)
rh	S	rh value in ppm - ash (spec, spec)
ru	S	ru value in ppm - ash (spec, spec)
sb	S	sb value in ppm - whole coal (anaa, ana)
sc	S	sc value in ppm - ash, uc (spec, ana-750527/spec)
se	S	se value in ppm - whole coal (anaa, ana)
sn	S	sn value in ppm - ash, uc (spec, ana-750701/spec)
ss	S	ss value in ppm - ash (spec)
sr	S	sr value in ppm - ash (spec, spec)
tl	S	tl value in ppm - ash (spec, spec)
tb	S	tb value in ppm - ash, uc (spec, ana-750527/spec)
th	S	th value in ppm - whole coal (anaa)
ti	S	ti value in ppm - ash (spec, spec)
tn	S	tn value in ppm - whole coal (anaa)
v	S	v value in ppm - ash (spec, spec)
y	S	y value in ppm - ash (spec, spec)
zb	S	zb value in ppm - ash, uc (spec, ana-750527/spec)
zn	S	zn value in ppm - ash (uetchem, uetchem)
zr	S	zr value in ppm - ash (spec, spec)

For the analytical methods used for an element have changed for a laboratory, the methods are given in order of oldest to newest e.g. (spec, ana-750527, uetchem-740819) with date of conversion of ash or whole coal basis - yr, mo, dy

across types of analyses

- uetchem = wet chemical analysis
- u numbers numbers on ash except hg & f
- ana = numbers on ash except na, f, hg, & sb
- anaa = instrumental neutron activation analysis on whole coal
- na = delayed neutron activation analysis on whole coal
- nrf = x-ray fluorescence
- u numbers on ash except cl & p
- w numbers on ash except so
- spec = spectrographic on ash
- for d numbers optical emission for d numbers six-step

additional characteristics based on the values contained in the 370 raw data elements. As of October 1982, the data base contains approximately 1,400 coal and associated rock samples. Samples are well distributed throughout the U.S. and represent all coal provinces except Alaska. In addition to the analytical data contained in the data base, the companion Penn State Coal Sample Bank contains carefully preserved physical samples of coal which are available for use by various research groups (3). A detailing of the raw data items included in the data base is presented in Table I-4.

TABLE I-4. PENN STATE COAL DATA BASE DATA ITEMS

1) SAMPLE AND SAMPLING INFORMATION.		9) ANALYSIS FOR SULFUR AND SULFUR FORMS.	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME		TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1	6 PROC NUMBER	1	87 PYRITIC SULFUR (DRY)
2	7 COLLECTOR	2	88 SULFATE SULFUR (DRY)
3	8 COLLECTOR NUMBER	3	89 ORGANIC SULFUR (DRY)
4	9 COLLECTION DATE	4	90 TOTAL SULFUR (DRY)
5	10 SAMPLE TYPE	-1	
6	11 SAMPLE QUALIFIER	10) ASH FUSION ANALYSIS.	
7	12 HARDNESS	TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
8	13 SIZE	1	91 INITIAL DEFORMATION TEMPERATURE (RED.)
9	14 SPECIFIC GRAVITY	2	92 SOFTENING TEMPERATURE (RED.)
10	15 SAMPLE RESERVE	3	93 HEMISPHERE TEMPERATURE (RED.)
11	16 SAMPLE INFORMATION	4	94 FLUID TEMPERATURE (RED.)
12	17 REPORTED NAME	5	95 INITIAL DEFORMATION (OXID.)
13	18 SEAM NAME	6	96 SOFTENING TEMPERATURE (OXID.)
14	19 ALTERNATE SEAM NAME	7	97 HEMISPHERE TEMPERATURE (OXID.)
15	20 SEAM THICKNESS	8	98 FLUID TEMPERATURE (OXID.)
16	21 THICKNESS SAMPLED	-1	
17	22 CORE RECOVERY	11) GEISELER PLASTICITY DATA.	
18	23 CORE DIAMETER	TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
-1		1	100 MAXIMUM FLUIDITY
2) GEOGRAPHIC INFORMATION.		2	101 INITIAL SOFTENING TEMPERATURE
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME		3	102 SOLIDIFICATION TEMPERATURE
1	24 COUNTRY	4	103 FLUID TEMPERATURE RANGE
2	25 STATE	5	104 PLASTOMETER TYPE
3	26 NEAREST TOWN	-1	
4	27 COUNTY	12) PHYSICAL PROPERTIES.	
5	28 TOWNSHIP	TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
6	29 ZIP CODE	1	105 FREE SWELLING INDEX
7	30 QUADRANGLE	2	106 GRAY KING CORE TYPE
8	31 LATITUDE	3	107 HARDGROVE GRINDABILITY
9	32 LONGITUDE	4	108 VICKERS MICROHARDNESS
10	33 COAL PROVINCE	5	109 SURFACE AREA - NITROGEN
11	34 COAL REGION	6	110 SURFACE AREA - CO ₂
12	35 COAL FIELD	7	111 HELIUM DENSITY
-1		8	112 MERCURY DENSITY
3) GEOLOGIC INFORMATION.		9	113 WATER DENSITY
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME		10	114 SPECIFIC GRAVITY
1	36 GEOLOGIC SYSTEM (AGE)	11	115 MICROPORE VOLUME
2	37 GEOLOGIC SERIES	12	116 MACROPORE VOLUME
3	38 LEVEL IN SYSTEM	13	117 TOTAL PORE VOLUME
4	39 LEVEL IN SERIES	14	118 PORE SIZE DISTRIBUTION
5	40 GROUP	-1	
6	41 FORMATION	13) PETROGRAPHIC ANALYSIS - LOW RANK COALS.	
7	42 OVERBURDEN LITHOLOGY	TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
8	43 FLOOR LITHOLOGY	1	119 TERPENTINE
-1		2	120 ULMINITE
4) SEAM STRATA INFORMATION.		3	121 ATYRINITE
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME		4	122 UMBRINITE
1	44 STRATUM I THICKNESS	5	123 GELINITE
2	45 STRATUM I LITHOTYPE	6	124 COMPOUNDINITE
3	46 STRATUM II THICKNESS	7	125 SPORINITE
4	47 STRATUM II LITHOTYPE	8	126 CUTINITE
5	48 STRATUM III THICKNESS	9	127 RESINITE
6	49 STRATUM III LITHOTYPE	10	128 EXUDATINITE
7	50 STRATUM IV THICKNESS	11	129 FLUORINITE
8	51 STRATUM IV LITHOTYPE	12	130 BITUMINITE
9	52 STRATUM V THICKNESS	13	131 ALGINITE
10	53 STRATUM V LITHOTYPE	14	132 LIPTODETRINITE
11	54 STRATUM VI THICKNESS	15	133 FUSINITE
12	55 STRATUM VI LITHOTYPE	16	134 SEMIFUSINITE
13	56 STRATUM VII THICKNESS	17	135 NACRINITE
14	57 STRATUM VII LITHOTYPE	18	136 MICRINITE
15	58 STRATUM VIII THICKNESS	19	137 SCLEROTINITE
16	59 STRATUM VIII LITHOTYPE	20	138 INERTODETRINITE
17	60 STRATUM IX THICKNESS	-1	
18	61 STRATUM IX LITHOTYPE	14) PETROGRAPHIC ANALYSIS - HIGH RANK COALS.	
19	62 STRATUM X THICKNESS	TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
20	63 STRATUM X LITHOTYPE	1	139 VITRINITE
-1		2	140 PSEUDOVITRINITE
5) MINE INFORMATION.		3	141 FUSINITE
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME		4	142 SEMIFUSINITE
1	64 MINE NAME	5	143 NACRINITE
2	65 MINING METHOD	6	144 MICRINITE
3	66 MINE RESERVES	7	145 SCLEROTINITE
4	67 MINE PRODUCTION	8	146 SPORINITE
5	68 MINE LIFE EXPECTANCY	9	147 CUTINITE
6	69 OVERBURDEN THICKNESS (FEET)	10	148 RESINITE
7	70 OVERBURDEN THICKNESS (INCHES)	11	149 EXUDATINITE
-1		12	150 FLUORINITE
6) OTHER CHEMICAL DATA.		13	151 BITUMINITE
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME		14	152 ALGINITE
1	71 CARBON DIOXIDE CONTENT (DRY)	15	153 LIPTODETRINITE
2	72 SULFUR AS SULFATE IN ASH (DRY)	-1	
3	73 OXYGEN AS COOH (MILLIEQUIVALENTS/GRAM OF DRY COAL)	15) REFLECTANCE ANALYSIS.	
4	74 OXYGEN AS OH (1% OF DRY COAL)	TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
5	75 INFRARED ANALYSIS AVAILABILITY	1	154 TYPE OF REFLECTANCE ANALYSIS
-1		2	155 VITRINITE: HIGH RO VALUE
7) PROXIMATE ANALYSIS.		3	156 LOW RO VALUE
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME		4	157 MEAN-MAX RO VALUE
1	76 EQUILIBRIUM MOISTURE	5	158 STANDARD DEVIATION
2	77 MOISTURE - AS RECEIVED	6	159 PSEUDOVITRINITE: HIGH RO VALUE
3	78 ASH CONTENT (DRY)	7	160 LOW RO VALUE
4	79 VOLATILE MATTER CONTENT (DRY)	8	161 MEAN-MAX RO VALUE
5	80 FIXED CARBON CONTENT (DRY)	9	162 STANDARD DEVIATION
6	81 CALORIFIC VALUE (DRY)	10	163 ULMINITE: HIGH RO VALUE
-1		11	164 LOW RO VALUE
8) ULTIMATE ANALYSIS.		12	165 MEAN-MAX RO VALUE
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME		13	166 STANDARD DEVIATION
1	82 CARBON CONTENT (DRY)	14	167 VITRINITE: HIGH RO VALUE
2	83 HYDROGEN CONTENT (DRY)	15	168 LOW RO VALUE
3	84 NITROGEN CONTENT (DRY)	16	169 MEAN-MAX RO VALUE
4	85 CHLORINE CONTENT (DRY)	17	170 STANDARD DEVIATION
5	86 OXYGEN CONTENT (DRY)		

TABLE I-4. (Continued)

16) HYDROLYZABLE NITROGEN	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 0 171 STEP	
2 0 172 STEP	
3 0 173 STEP	
4 0 174 STEP	
59 0 229 STEP 59	
17) MINERALOGICAL ANALYSIS (OGONMAN)	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 26 239 KAOLINITE	
2 26 231 ILLITE	
3 26 232 MUSCOVITE	
4 26 233 CHLORITE	
5 26 234 MONTMORILLONITE	
6 26 235 MIXED CLAYS	
7 26 236 CALCITE	
8 26 237 ARAGONITE	
9 26 238 DOLOMITE	
10 26 239 ANKERITE	
11 26 240 SIDERITE	
12 26 241 QUARTZ	
13 26 242 GYPSUM	
14 26 243 PYRITE	
15 26 244 JAROSITE	
16 26 245 HEMATITE	
17 26 246 RUTILE	
18 26 247 THEOPHANE	
19 26 248 FLUORAPATITE	
-1	
18) MINERALOGICAL ANALYSIS (NCL)	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 0 249 QUARTZ	
2 0 250 PYRITE	
3 0 251 CALCITE	
4 0 252 GYPSUM	
5 0 253 KAOLINITE	
6 0 254 MONTMORILLONITE + ILLITE + MIXED LAYER CLAY	
7 0 255 MONTMORILLONITE + ILLITE + MIXED LAYER CLAY	
8 0 256 MONTMORILLONITE + MIXED LAYER CLAYS	
9 0 257 ILLITE + MIXED LAYER CLAYS	
10 0 258 MONTMORILLONITE	
11 0 259 ILLITE	
12 0 260 MIXED LAYER CLAYS	
13 0 261 FELDSPAR	
14 0 262 MINOR FE SULFATES	
-1	
19) MAJOR AND MINOR ELEMENT ANALYSIS	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 0 263 SiO2 CONTENT	
2 0 264 AL2O3 CONTENT	
3 0 265 TiO2 CONTENT	
4 0 266 Fe2O3 CONTENT	
5 0 267 MnO CONTENT	
6 0 268 CaO CONTENT	
7 0 269 Na2O CONTENT	
8 0 270 K2O CONTENT	
9 0 271 P2O5 CONTENT	
10 0 272 SO3 CONTENT	
-1	
20) ASH ANALYSIS	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 0 273 ASH CONTENT (LOW TEMPERATURE - NCL)	
2 0 274 ASH CONTENT (LOW TEMPERATURE - OGL)	
3 0 275 ASH CONTENT (LOW TEMPERATURE - O'GONMAN)	
4 0 276 ASH CONTENT (HIGH TEMPERATURE NCL)	
5 0 277 % H2O - DIRECT	
6 0 278 TEMPERATURE OF ASH ANALYSIS (DEG. C.)	
7 0 279 MOISTURE CONTENT OF COAL SAMPLE	
-1	
21) TRACE ELEMENT ANALYSIS	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 0 280 AG CONTENT	
2 0 281 AR CONTENT	
3 0 282 BA CONTENT	
4 0 283 BR CONTENT	
5 0 284 BI CONTENT	
6 0 285 CE CONTENT	
7 0 286 CO CONTENT	
8 0 287 CR CONTENT	
9 0 288 CU CONTENT	
10 0 289 GA CONTENT	
11 0 290 GE CONTENT	
12 0 291 LA CONTENT	
13 0 292 LI CONTENT	
14 0 293 NH CONTENT	
15 0 294 NO CONTENT	
16 0 295 NI CONTENT	
17 0 296 PB CONTENT	
18 0 297 PR CONTENT	
19 0 298 RB CONTENT	
20 0 299 SC CONTENT	
21 0 300 SR CONTENT	
22 0 301 TH CONTENT	
23 0 302 TR CONTENT	
24 0 303 U CONTENT	
25 0 304 V CONTENT	
26 0 305 Y CONTENT	
27 0 306 ZN CONTENT	
28 0 307 ZR CONTENT	
29 0 308 ZN CONTENT	
22) VOLATILE TRACE ELEMENTS	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 0 309 AS CONTENT	
2 0 310 BR CONTENT	
3 0 311 CD CONTENT	
4 0 312 CL CONTENT	
5 0 313 F CONTENT	
6 0 314 HG CONTENT	
7 0 315 SB CONTENT	
8 0 316 SE CONTENT	
-1	
23) PREPARATION DATA	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 0 317 1.35 FLOAT: YIELD	
2 0 318	ASH
3 0 319	SULFUR
4 0 320	VITRINITE
5 0 321	LIPITINITE
6 0 322	INERTINITE
7 0 323 1.35 X 1.45: YIELD	
8 0 324	ASH
9 0 325	SULFUR
10 0 326	VITRINITE
11 0 327	LIPITINITE
12 0 328	INERTINITE
13 0 329 1.45 X 1.55: YIELD	
14 0 330	ASH
15 0 331	SULFUR
16 0 332	VITRINITE
17 0 333	LIPITINITE
18 0 334	INERTINITE
19 0 335 1.55 X 1.65: YIELD	
20 0 336	ASH
21 0 337	SULFUR
22 0 338	VITRINITE
23 0 339	LIPITINITE
24 0 340	INERTINITE
25 0 341 1.65 SINK: YIELD	
26 0 342	ASH
27 0 343	SULFUR
28 0 344	VITRINITE
29 0 345	LIPITINITE
30 0 346	INERTINITE
-1	
24) GASIFICATION DATA	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 0 347 CHAR REACTIVITY (AIR)	
2 0 348 TEMPERATURE (AIR DEG. C)	
3 0 349 PRESSURE (AIR ATM.)	
4 0 350 CHAR REACTIVITY (CO2)	
5 0 351 TEMPERATURE (CO2 DEG. C)	
6 0 352 PRESSURE (CO2 ATM.)	
7 0 353 CHAR REACTIVITY (H2)	
8 0 354 TEMPERATURE (H2 DEG. C)	
9 0 355 PRESSURE (H2 ATM.)	
-1	
25) CARBONIZATION DATA	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 0 356 MEASURED STABILITY	
2 0 357 MEASURED NUCON 48	
-1	
26) ANALYSIS LOG	
TABLE ENTRY-TABLE INDEXED-LOCATION-NAME	
1 28 358 AS RECEIVED MOISTURE: AGENCY	
2 0 359	DATE
3 28 360 EQUILIBRIUM MOISTURE: AGENCY	
4 0 361	DATE
5 28 362 PROXIMATE ANALYSIS: AGENCY	
6 0 363	DATE
7 28 364 ULTIMATE ANALYSIS: AGENCY	
8 0 365	DATE
9 28 366 SULFUR FORMS: AGENCY	
10 0 367	DATE
11 28 368 FREE SWELLING INDEX: AGENCY	
12 0 369	DATE
13 28 370 GEISLER PLASTICITY: AGENCY	
14 0 371	DATE
15 28 372 DIRECT MINERAL MATTER: AGENCY	
16 0 373	DATE
17 28 374 GRAY KING COKE TYPE: AGENCY	
18 0 375	DATE

APPENDIX II

ELEMENT REMOVAL DATA FOR 44 COALS
SUBJECTED TO GRAVITY SEPARATION

TABLE II-1. SAMPLE DESCRIPTION

ID	REGION	PROVINCE	FORMATION	SEAM	STATE	COUNTY	RAINF.	TOP SIZE (in.)	BOT SIZE (in.)	SG
Appalachian Province: Monongahela Group										
DOE1	4N	AP	MONONGAHEL	PITTSBURGH	PA	ALLEGHENY	HVAB	0.05 ^a	0.00	1.60
DOE2	4N	AP	MONONGAHEL	WAYNESBURG	OH	BELMONT	HV B	0.05	0.00	1.60
10R	4N	AP	MONONGAHEL	SEWICKLEY	OH	NOBLE	HVBB	1.25 ^b	0.02 ^d	1.55
18892	4N	AP	MONONGAHEL	PITTSBURGH	WV			0.38 ^c	0.02	1.60
19R	4N	AP	MONONGAHEL	PITTSBURGH	PA	WASHINGTON	HVAB	1.25	0.02	1.55
22R	4N	AP	MONONGAHEL	SEWICKLEY	PA	GREENE	HVAB	1.25	0.02	1.60
23R	4N	AP	MONONGAHEL	PITTSBURGH	OH	BELMONT	HVBB	1.25	0.02	1.60
24R	4N	AP	MONONGAHEL	PITTSBURGH	WV	HARRISON	HVAB	1.25	0.02	1.60
9R	4N	AP	MONONGAHEL	PITTSBURGH	WV	HARRISON	HVAB	1.25	0.02	1.55
Appalachian Province: Allegheny Formation										
DOE3	4M	AP	ALLEGHENY	U FREEPORT	MD	GARRETT	HV B	0.05	0.00	1.60
1R	4M	AP	ALLEGHENY	L FREEPORT	PA	INDIANA	HVAB	1.25	0.02	1.55
20R	4M	AP	ALLEGHENY	L KITTANNG	PA	CAMBRIA	LVB	1.25	0.02	1.55
21R	4M	AP	ALLEGHENY	L KITTANNG	PA	CAMBRIA	HVB	1.25	0.02	1.60
8R	4M	AP	ALLEGHENY	L KITTANNG	WV	NICHOLAS	HVAB	1.25	0.02	1.55
Appalachian Province: Pottsville Group										
DOE4	4S	AP	KANAWHA	HAZARD 4	KY	BELL	HV B	0.05	0.00	1.60
11R	4S	AP	POCAHONTAS	POCHNTAS 3	WV	MCDOWELL	LVB	1.25	0.02	1.55
12R	4S	AP	KANAWHA	STOCKTON	WV	LOGAN	HVAB	1.25	0.02	1.55
13R	4S	AP	NEW RIVER	SEWELL	WV	RALEIGH	HVB	1.25	0.02	1.55
14R	4S	AP	NEW RIVER	SEWELL	AL	WALKER	HVAB	1.25	0.02	1.55
17R	4S	AP	KANAWHA	L ELKHORN	WV	WISE	HVAB	1.25	0.02	1.55
18R	4S	AP	KANAWHA	V ELKHORN 3	KY	KNOTT	HVAB	1.25	0.02	1.55
18889	4S	AP	NEW RIVER	BLUE CREEK	AL			0.38	0.02	1.60
18890	4S	AP	POCAHONTAS	POCHNTAS 4	WV			0.38	0.02	1.60
Interior Province										
DOE5	6	IN	ALLEGHENY	ILLINOIS 6	IL	FERRY	HVBB	0.05	0.00	1.60
DOE6	6	IN	ALLEGHENY	ILLINOIS 5	IL	FERRY	HV B	0.05	0.00	1.60
DOE7	6	IN	ALLEGHENY	DEKOVEN	KY	OHIO	HV B	0.05	0.00	1.60
15R	6	IN	ALLEGHENY	ILLINOIS 5	KY	NUHLENBURG	HVBB	1.25	0.02	1.55
16R	6	IN	ALLEGHENY	ILLINOIS 5	IL	FULTON	HVBB	1.25	0.02	1.55
18090	6	IN	ALLEGHENY	DAVIS	IL			0.38	0.02	1.60
18092	6	IN	ALLEGHENY	DEKOVEN	IL			0.38	0.02	1.60
18121	6	IN	ALLEGHENY	ILLINOIS 6	IL			0.38	0.02	1.60
18133	6	IN	ALLEGHENY	ILLINOIS 2	IL			0.38	0.02	1.60
18562	6	IN	ALLEGHENY	ILLINOIS 6	IL			0.38	0.02	1.60
2R	6	IN	ALLEGHENY	ILLINOIS 6	IL	FRANKLIN	HVBB	1.25	0.02	1.55
25R	6	IN	ALLEGHENY	ILLINOIS 6	IL	WILLIAMSON	HVBB	1.25	0.02	1.60
26R	6	IN	ALLEGHENY	ILLINOIS 5	KY	HOPKINS	HVBB	1.25	0.02	1.60
Northern Great Plains Province										
4R	11	NGF	PALEOCENE	BEULAN-2AP	ND	MERCER	LIGA	1.25	0.02	1.55
3R	12	NGP	PALEOCENE	ROSEBUD	MT	ROSEBUD	SUBB	1.25	0.02	1.55
Rocky Mountain Province										
6R	18	RM	CRETACEOUS	ADAVILLE 1	WY	LINCOLN	SUBA	1.25	0.02	1.55
7R	19	RM	CRETACEOUS	CSTL GAT D	UT	CARBON	HVAB	1.25	0.02	1.55
DOE8	BLKMS	RM	CRETACEOUS	BLACK MESA	AZ	NAVAJO	SUB	0.38	0.00	1.60
DOE9	21	RM	CRETACEOUS	SAN JUAN 8	NM	SAN JUAN	SUB	0.38	0.00	1.60
19014	BLKMS	RM	CRETACEOUS	BLACK MESA	AZ			0.38	0.02	1.60
DOE10	24	RM	CRETACEOUS	ROCK SPRNG	WY	SWEETWATER	HVBB	0.05	0.00	1.60

^a14 mesh = 0.02169 in. = 1.18 mm^b1½ in. = 31.75 mm^c3/8 in. = 9.53 mm^d28 mesh = 0.0234 in. = 0.60 mm

TABLE II-2. MAJOR SPECIES REMOVAL (PERCENT)

ID	REGION	ORS	PYS	TOS	ASH	BTU	AL	CA	MG	K	FE	MA	SI	TI
DOE1	4N	-	-	22.6	42.5	-	-	-	-	-	-	-	-	-
DOE2	4N	-	74.5	53.9	43.9	9.5	-	-	-	-	-	-	-	-
10R	4N	4.4	25.9	21.0	36.5	8.6	34.7	35.7	44.0	41.3	36.5	37.0	36.6	37.1
18892	4N	1.0	16.8	9.0	30.1	2.7	30.2	27.2	25.6	43.7	21.0	28.1	38.8	66.1
19R	4N	9.8	38.2	30.1	84.6	12.3	85.0	83.8	88.7	88.1	62.4	87.1	87.4	84.7
22R	4N	-	60.4	50.0	76.7	8.5	74.1	82.9	86.4	83.5	74.8	74.5	77.6	72.1
23R	4N	-	30.5	22.9	70.6	5.1	74.6	72.1	76.1	83.5	40.6	64.5	76.9	76.5
24R	4N	-	21.7	15.3	17.7	1.4	9.1	24.4	18.3	19.2	25.1	5.1	13.7	12.0
9R	4N	0.2	51.3	40.1	62.4	0.1	55.8	61.2	58.0	77.5	57.7	40.3	68.2	59.6
AVERAGE		3.9	39.9	29.4	51.7	6.0	51.9	55.3	56.7	62.4	45.4	48.1	57.3	58.3
DOE3	4M	-	69.7	50.9	63.0	5.7	-	-	-	-	-	-	-	-
1R	4M	6.3	69.5	57.7	71.3	3.3	67.4	50.0	77.8	78.5	75.0	61.7	71.8	62.1
20R	4M	22.9	80.7	72.3	86.5	12.4	83.4	56.8	90.4	92.5	83.0	85.3	88.7	83.1
21R	4M	-	70.5	57.5	61.7	6.3	56.5	32.4	65.3	66.9	70.6	63.5	62.7	55.7
8R	4M	12.4	40.1	25.1	84.4	10.1	81.1	66.3	86.7	91.8	74.2	76.0	85.4	81.0
AVERAGE		13.9	66.1	52.7	73.4	7.6	72.1	51.4	80.1	82.4	75.7	71.6	77.6	70.5
DOE4	4S	-	68.7	34.8	81.2	8.3	-	-	-	-	-	-	-	-
11R	4S	5.7	44.6	14.9	83.8	6.7	80.7	62.8	84.4	94.5	69.0	78.4	86.8	79.8
12R	4S	20.7	47.0	33.7	86.9	20.9	84.0	85.9	91.2	91.6	87.3	89.1	87.7	85.1
13R	4S	20.8	79.0	66.2	95.4	17.7	95.0	87.0	96.7	96.9	89.8	90.9	96.1	95.1
14R	4S	1.7	31.1	18.4	69.1	8.4	66.2	57.6	70.9	73.8	63.7	71.3	70.0	65.2
17R	4S	15.0	39.8	21.3	79.6	8.5	74.6	64.6	87.7	87.9	81.2	83.6	82.1	72.1
18R	4S	5.7	30.2	22.1	87.6	0.9	87.7	53.5	89.8	94.5	74.7	83.3	90.7	85.7
18889	4S	1.0	40.5	3.7	34.7	2.9	30.7	8.9	62.7	48.0	27.7	40.5	48.0	24.1
18890	4S	2.0	91.0	25.8	49.9	4.6	58.7	29.6	45.4	57.1	30.0	21.8	72.0	52.8
AVERAGE		9.1	52.4	26.8	74.2	8.8	71.2	56.2	78.6	80.5	65.4	69.9	79.2	70.0
DOE5	6	-	64.9	32.5	55.2	6.3	-	-	-	-	-	-	-	-
DOE6	6	-	71.7	26.4	37.5	3.5	-	-	-	-	-	-	-	-
DOE7	6	-	-	35.7	32.4	-	-	-	-	-	-	-	-	-
15R	6	-11.5	45.7	34.5	67.4	1.3	66.4	65.2	85.0	80.0	63.5	79.1	67.8	61.8
16R	6	-1.4	37.3	31.8	62.5	-2.5	58.7	63.1	74.3	66.2	64.2	68.2	62.2	55.5
18090	6	0.1	76.5	56.4	40.1	-	8.5	16.6	36.1	4.2	82.2	17.0	14.6	5.7
18092	6	2.8	59.4	51.7	33.4	-	11.2	2.5	9.0	15.5	20.1	4.5	11.7	5.1
18121	6	5.6	69.3	41.7	54.9	-	55.5	89.1	46.8	74.9	89.6	54.6	72.7	79.4
18133	6	0.1	42.6	33.1	34.9	-	34.0	77.0	-	30.6	47.6	13.6	34.4	22.7
18562	6	2.3	77.2	40.6	22.9	3.1	25.4	3.4	31.9	19.1	71.6	23.2	35.4	37.7
2R	6	5.0	51.0	45.5	53.0	1.3	46.3	67.2	53.4	54.6	63.8	41.9	49.4	46.1
25R	6	-	48.5	38.3	66.1	4.2	53.3	97.8	75.4	57.0	59.9	62.9	57.2	47.8
26R	6	-	37.3	30.3	60.3	5.0	60.7	67.2	65.0	65.8	48.9	76.8	67.9	56.3
AVERAGE		0.4	56.8	38.3	47.7	2.8	42.0	55.4	53.0	46.8	61.1	44.2	47.3	41.8
4R	11	17.0	47.0	44.1	35.2	4.0	34.2	18.1	15.1	52.0	57.8	11.8	54.5	37.7
3R	12	13.0	59.9	55.0	45.9	6.5	37.5	8.3	16.6	65.5	79.0	23.9	49.3	46.6
AVERAGE		15.0	53.4	49.5	40.5	5.2	35.9	13.2	15.8	58.7	68.4	17.9	51.9	42.2
6R	18	-23.4	16.7	7.7	8.6	1.2	9.6	-8.3	-1.1	10.6	46.7	1.6	-3.4	-3.6
7R	19	-3.7	23.1	10.3	51.8	3.3	41.7	30.6	34.7	87.1	34.2	34.7	55.5	41.5
DOE8	BLKMS	-	13.6	6.2	30.7	1.7	-	-	-	-	-	-	-	-
DOE9	21	-	59.0	18.0	54.3	8.1	-	-	-	-	-	-	-	-
19014	BLKMS	0.2	17.0	1.2	7.1	0.5	4.2	1.7	1.4	4.3	2.2	0.9	13.1	7.7
DOE10	24	-	63.2	24.2	55.9	1.5	-	-	-	-	-	-	-	-
AVERAGE		-9.0	32.1	11.2	34.7	2.7	18.5	8.0	11.7	34.0	27.7	12.4	21.7	15.2

TABLE II-3. TRACE ELEMENT REMOVAL (PERCENT)

ID	REGION	AS	B	BE	CD	CL	CO	CR	CU	F	HG	HN	NI	P	PB	SB	SE	V	ZN
DOE1	4N	-	-	-	26.4	-	-	11.3	35.9	29.7	50.2	58.7	25.2	-	31.8	-	-	-	-
DOE2	4N	-	-	-	39.5	-	-	23.4	47.6	34.8	52.9	52.9	48.1	-	60.8	-	-	-	-
10R	4N	49.9	-	23.8	24.9	-7.2	-	26.9	23.1	38.2	37.7	43.3	28.5	55.3	30.6	30.3	37.8	24.1	32.9
18892	4N	18.3	3.3	9.4	12.2	-	14.4	43.7	32.9	-	11.8	24.0	24.4	4.4	14.2	29.0	15.3	22.5	14.1
19R	4N	74.6	-	59.3	63.9	-	72.9	73.0	78.7	76.7	44.3	87.4	60.5	73.8	78.1	-	63.6	65.7	75.5
22R	4N	71.4	46.8	65.6	69.8	32.0	72.4	69.5	67.9	78.7	38.4	87.4	66.1	83.6	67.6	37.1	50.6	65.6	77.6
23R	4N	60.8	26.7	49.2	64.9	37.6	57.0	61.3	65.2	70.2	26.6	60.0	59.4	86.8	70.0	30.7	44.1	53.7	69.0
24R	4N	28.8	1.8	8.0	44.6	3.0	13.7	9.3	10.7	12.1	17.8	14.3	14.1	15.0	17.5	10.5	15.6	9.4	16.3
9R	4N	66.8	-	43.9	36.7	-6.3	-	52.8	53.5	63.4	40.1	58.5	58.5	72.5	70.0	68.0	44.6	48.1	64.0
AVERAGE		52.9	19.6	37.0	42.5	11.8	46.1	41.2	46.2	50.5	35.5	54.0	42.8	55.9	49.0	34.2	38.8	41.3	49.9
DOE3	4H	-	-	-	32.3	-	-	37.3	48.2	61.3	48.6	56.4	41.8	-	66.2	-	-	-	-
1R	4H	80.8	-	40.6	40.1	-13.1	-	55.1	58.1	55.4	69.3	84.4	50.0	30.6	76.6	34.1	63.8	53.4	67.2
20R	4H	90.1	-	53.2	64.6	-	79.8	76.3	85.5	80.5	63.5	87.2	52.8	85.4	90.9	-	79.6	75.0	74.2
21R	4H	74.3	62.2	29.1	50.2	7.4	58.9	44.7	58.1	47.5	51.9	76.8	56.5	43.1	72.2	30.4	67.2	39.1	50.6
8R	4H	63.1	-	52.9	53.9	28.2	-	72.1	54.1	84.0	56.6	87.0	59.0	67.7	64.9	32.6	48.8	67.8	68.9
AVERAGE		77.1	62.2	44.0	48.2	7.5	69.3	57.1	60.8	65.7	58.0	78.4	52.0	56.7	74.1	32.4	64.8	58.8	65.2
DOE4	4S	-	-	-	22.9	-	-	70.3	42.2	81.8	48.6	79.8	44.3	-	59.2	-	-	-	-
11R	4S	60.7	-	48.3	58.5	-	37.7	77.7	53.7	87.1	45.6	84.3	49.1	82.9	69.2	26.6	38.1	74.0	82.7
12R	4S	85.3	-	58.7	76.9	-	41.3	80.9	65.9	84.0	66.3	93.9	61.4	84.0	76.8	45.7	51.7	76.8	82.8
13R	4S	82.9	-	75.8	88.7	32.1	87.2	92.8	77.8	92.0	79.1	97.2	88.0	87.7	91.5	-	73.0	85.3	91.3
14R	4S	74.6	-	47.1	55.1	-	39.1	56.9	53.8	55.0	57.3	71.9	45.1	31.2	60.4	-	52.8	64.7	64.8
17R	4S	72.3	-	46.9	34.9	-	46.7	69.8	56.3	77.5	36.6	92.1	51.5	72.9	65.4	-	43.7	68.7	82.7
18R	4S	59.9	-	20.7	53.3	-16.8	48.4	81.2	39.9	78.7	52.3	81.2	44.1	81.5	70.0	-	35.5	74.4	81.7
18889	4S	83.2	25.6	17.2	51.2	-	4.3	23.3	13.8	-	8.0	39.4	7.0	37.6	12.8	18.1	17.9	11.2	23.5
18890	4S	79.3	33.6	26.2	43.6	-	9.7	32.1	26.8	-	60.7	31.0	19.1	34.1	34.2	20.1	27.3	21.3	41.4
AVERAGE		74.8	29.6	42.6	53.9	7.6	39.3	65.0	47.8	79.5	50.5	74.5	45.5	64.0	60.0	27.6	42.5	59.5	68.9
DOE5	6	-	-	-	97.1	-	-	23.4	49.1	27.1	22.2	71.6	27.1	-	44.7	-	-	-	-
DOE6	6	-	-	-	85.9	-	-	14.6	8.3	19.4	22.3	84.3	13.6	-	13.0	-	-	-	-
DOE7	6	-	-	-	53.2	-	-	20.1	28.9	21.2	35.2	31.4	10.7	-	39.3	-	-	-	-
15R	6	54.4	-	39.7	68.4	17.1	66.7	62.6	65.7	68.3	38.9	84.2	70.9	92.3	66.5	-	34.0	41.2	67.3
16R	6	69.5	-	17.9	86.5	-	64.5	52.6	48.9	59.3	12.9	68.6	55.0	89.6	67.4	-	38.9	49.3	85.3
18090	6	59.6	1.5	5.1	100.0	-	22.7	17.8	13.9	-	74.4	34.4	20.6	30.4	64.7	17.0	8.5	8.5	8.5
18092	6	108.0	-	13.3	36.0	-	28.5	26.4	13.9	-	58.1	18.0	20.1	18.0	60.9	14.4	34.8	20.1	32.5
18121	6	60.3	13.3	22.7	69.0	-	59.3	34.6	44.1	-	75.8	64.9	31.6	40.0	59.1	34.5	40.4	35.1	80.6
18133	6	38.9	-	10.6	49.2	-	12.2	52.9	27.2	-	34.0	54.9	20.4	3.4	21.3	16.6	17.0	18.4	45.3
18562	6	72.5	4.2	24.3	40.6	-	19.0	19.5	8.7	-	19.3	12.0	21.4	147.2	21.3	17.2	43.5	11.3	36.3
2R	6	49.5	-	25.9	65.7	5.0	-	34.6	41.4	55.8	11.6	65.7	26.5	85.8	57.7	-18.7	25.1	19.6	48.0
25R	6	44.3	15.2	29.0	87.7	-31.7	36.4	60.3	53.3	66.5	12.9	88.7	44.2	93.6	51.8	32.0	65.0	43.9	86.3
26R	6	49.5	14.6	27.8	93.1	-2.3	39.6	55.9	54.7	54.1	23.0	64.1	46.2	67.9	51.4	19.2	41.4	45.1	82.8
AVERAGE		60.6	9.8	21.6	71.7	-3.0	38.8	36.6	35.2	46.2	33.9	57.1	31.4	66.8	47.6	16.5	34.9	29.2	57.3
4R	11	60.6	-	7.8	23.2	86.8	-	25.0	26.0	20.2	20.4	41.8	4.2	28.2	38.0	27.9	36.6	6.9	31.4
3R	12	76.7	-	16.0	42.0	13.0	-	43.8	30.1	35.2	50.6	19.8	6.4	19.0	43.7	58.5	55.1	25.4	62.1
AVERAGE		68.7	-	11.9	32.6	49.9	-	34.4	28.1	27.7	35.5	30.8	5.3	23.6	40.9	43.2	45.9	16.2	46.8
6R	18	41.0	-	-38.2	50.7	75.3	-	34.4	8.2	0.1	3.0	0.1	30.3	19.0	48.2	19.8	31.1	-9.8	41.7
7R	19	49.6	-	22.3	64.1	-7.6	-	43.1	22.4	34.3	41.2	62.8	34.8	11.5	43.9	52.9	10.3	31.4	59.0
DOE8	BLKHS	-	-	-	17.9	-	-	9.4	24.2	22.4	28.2	4.2	4.2	-	25.7	-	-	-	-
DOE9	21	-	-	-	59.0	-	-	19.6	24.3	36.9	53.1	80.4	18.0	-	49.4	-	-	-	-
19014	BLKHS	6.5	0.9	1.3	2.0	-	3.0	4.5	0.3	-	5.2	2.4	3.7	2.3	2.4	0.3	2.8	1.1	1.4
DOE10	24	-	-	-	18.2	-	-	30.0	3.4	27.8	19.1	71.9	0.2	-	33.7	-	-	-	-
AVERAGE		32.3	0.9	-4.9	35.3	33.8	3.0	23.5	13.8	24.3	25.0	37.0	15.2	10.9	33.9	24.3	14.7	7.6	34.1

APPENDIX III

REGRESSION ANALYSIS OF TRACE ELEMENT REMOVAL
DATA AS A FUNCTION OF ASH AND SULFUR REMOVALS

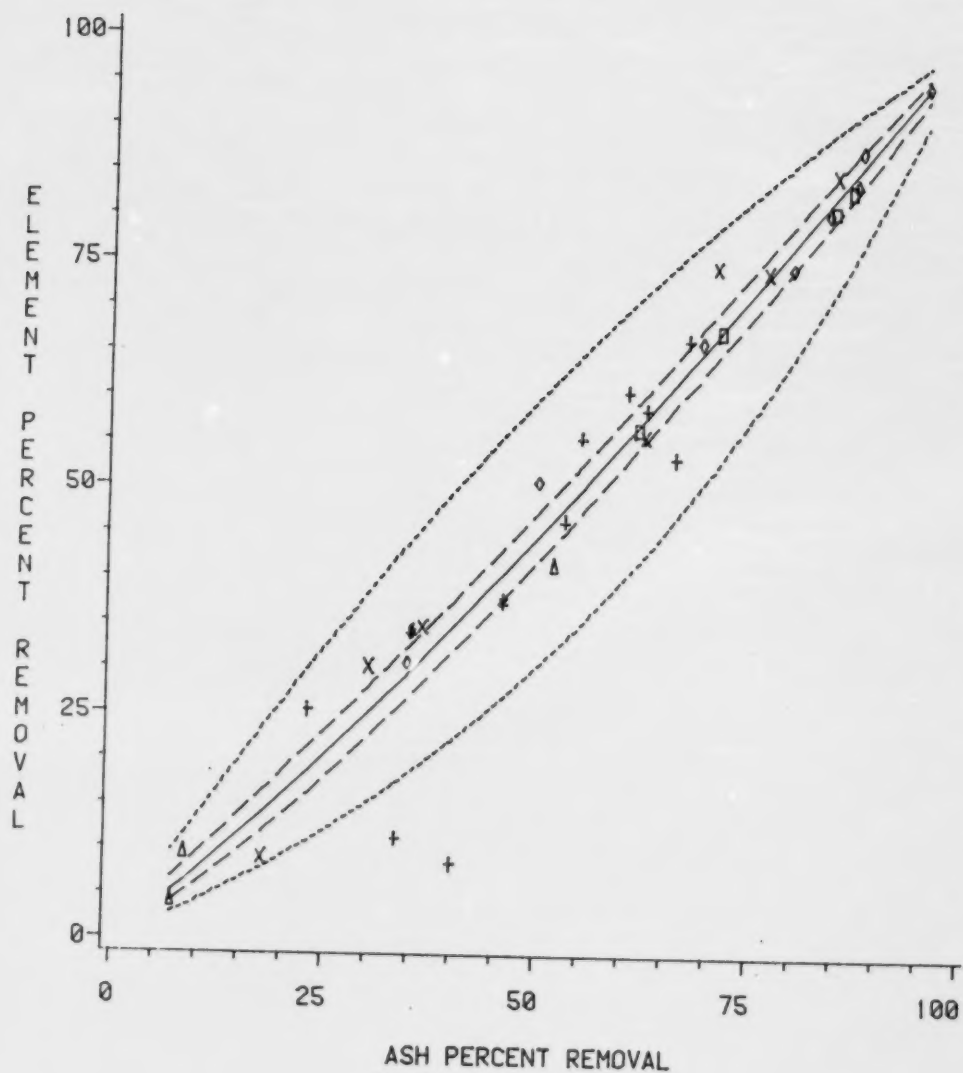
SECTION III-1

VERSUS ASH

+ INTERIOR
* N GRT PLAIN
x AP MONON
□ AP ALLEG
◇ AP POTTSVILLE
△ ROCKY MTN

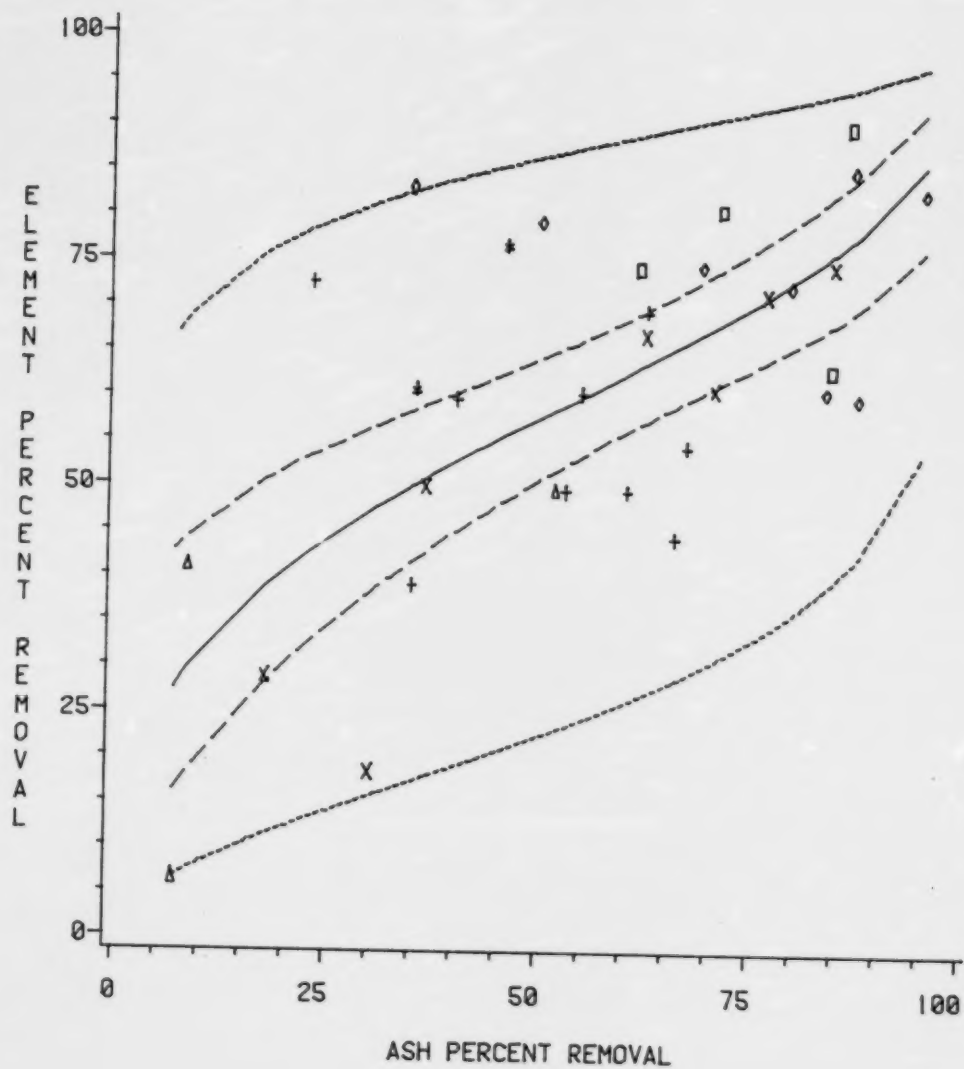
—— MEAN LINE
---- 95% CI MEAN
.... 95% CI INDIVIDUAL

ELEMENT=AL



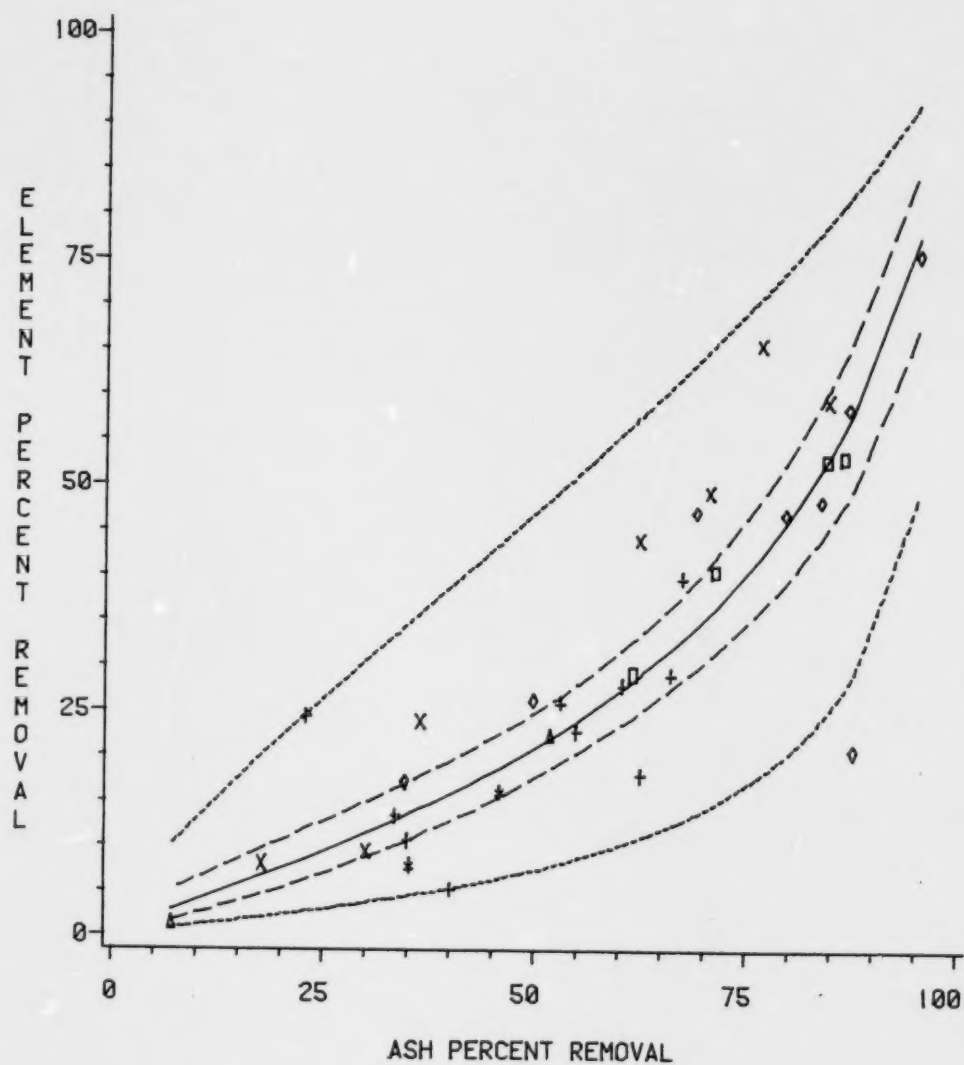
Regression Curve for Removal of Aluminum as a
Function of Ash Removal

ELEMENT=AS

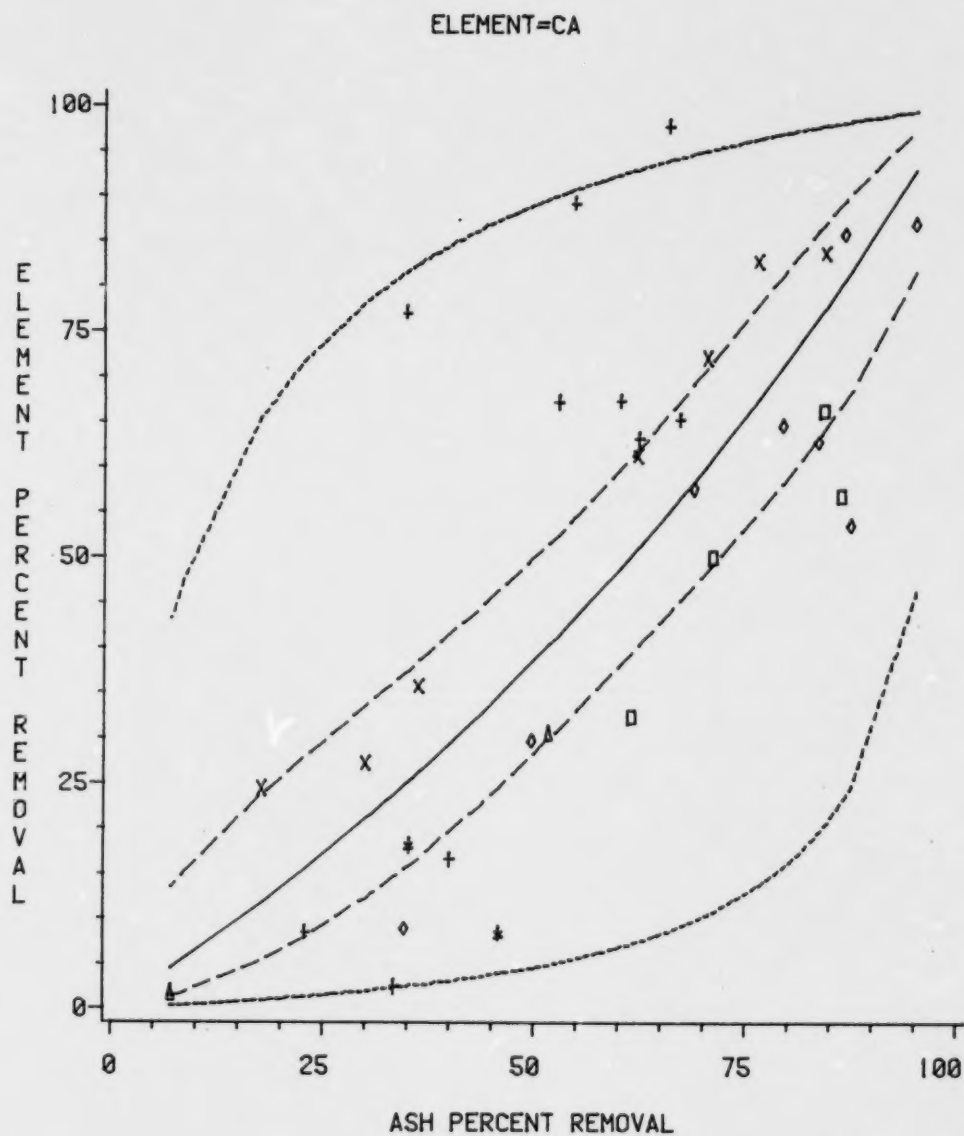


Regression Curve for Removal of Arsenic as a Function of Ash Removal

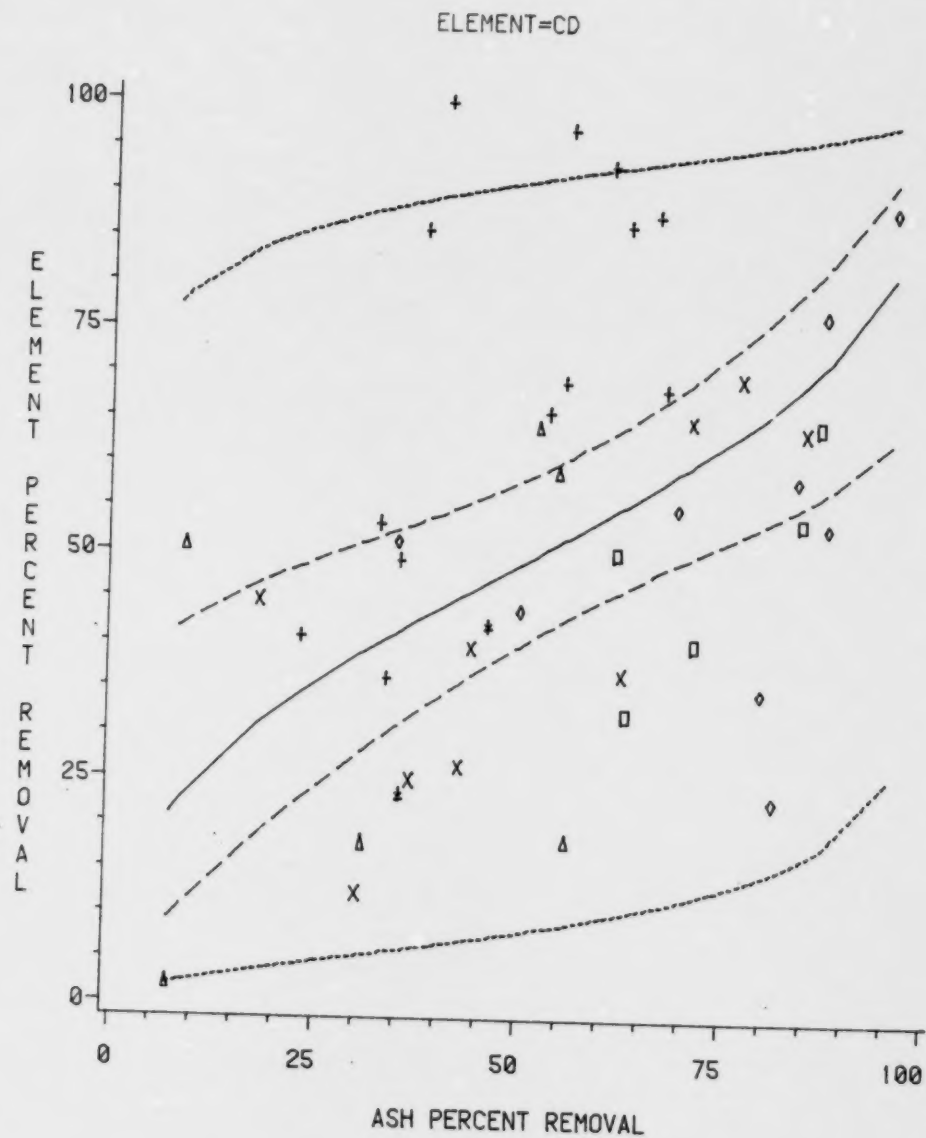
ELEMENT=BE



Regression Curve for Removal of Beryllium as a
Function of Ash Removal

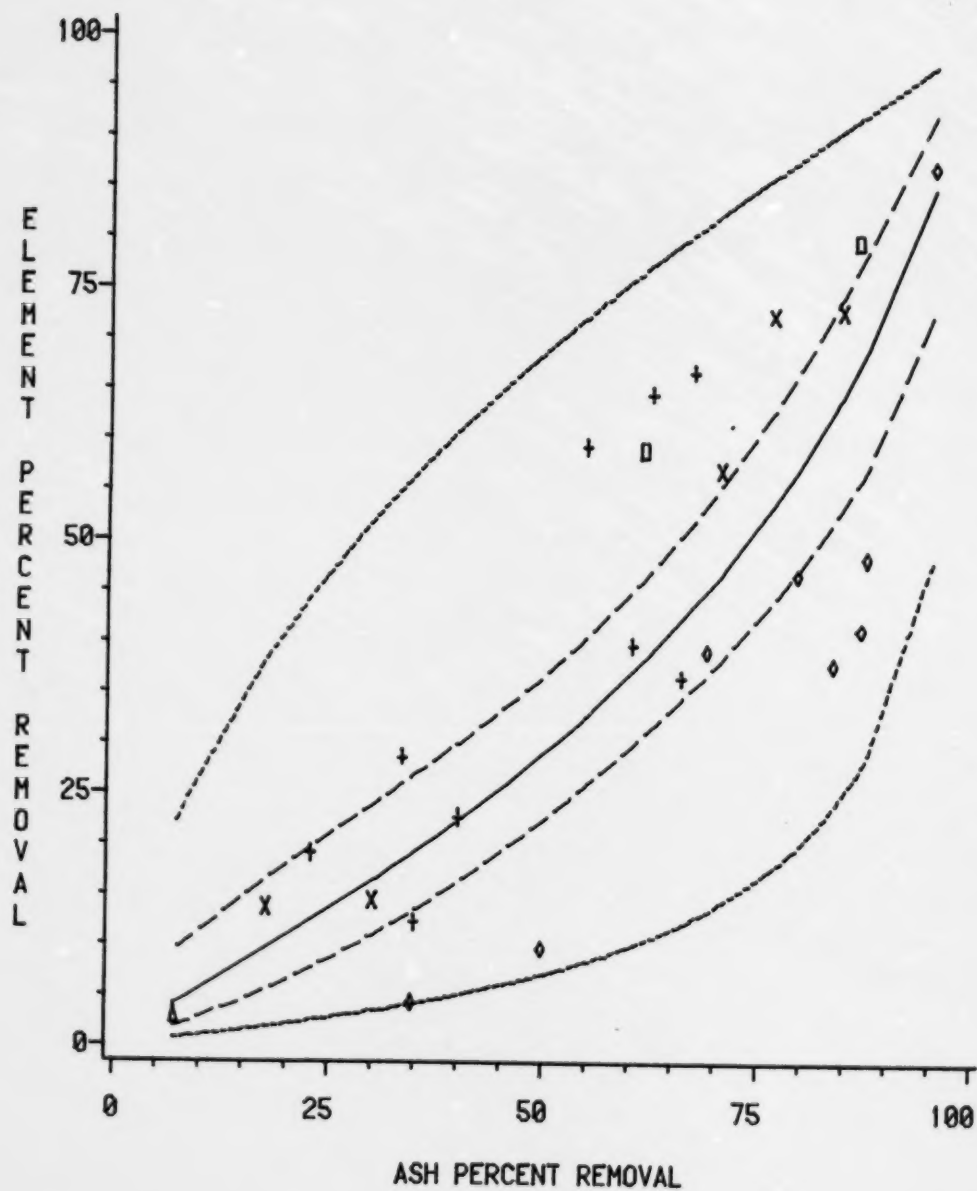


Regression Curve for Removal of Calcium as a
Function of Ash Removal



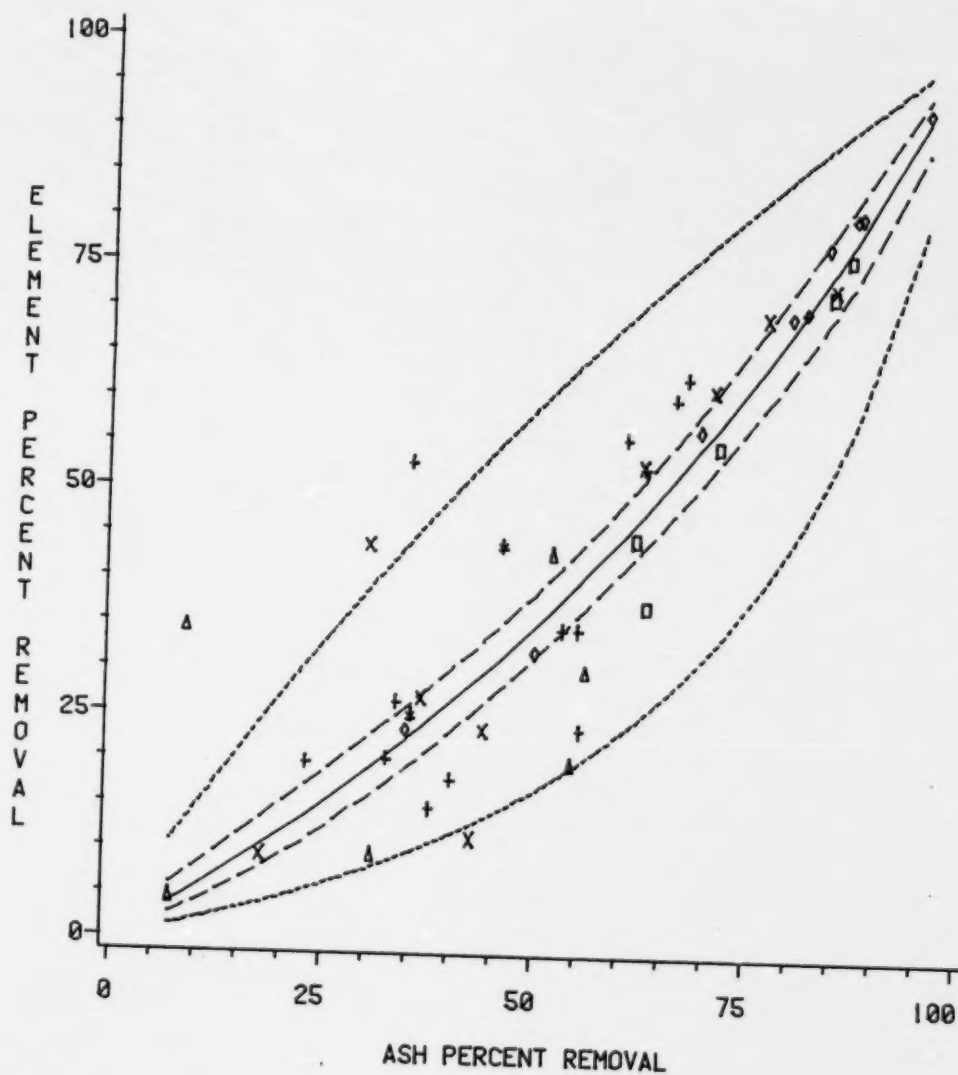
Regression Curve for Removal of Cadmium as a
Function of Ash Removal

ELEMENT=CO



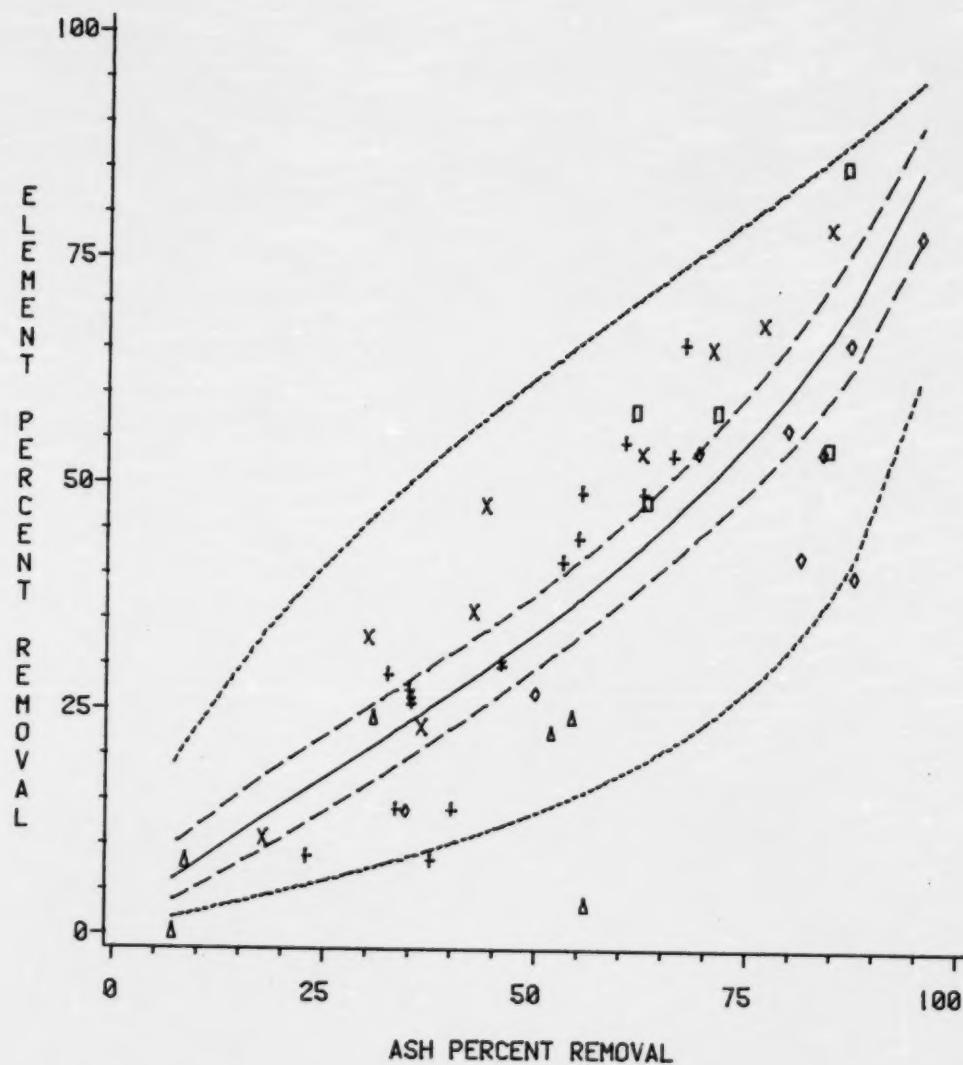
Regression Curve for Removal of Cobalt as a
Function of Ash Removal

ELEMENT=CR



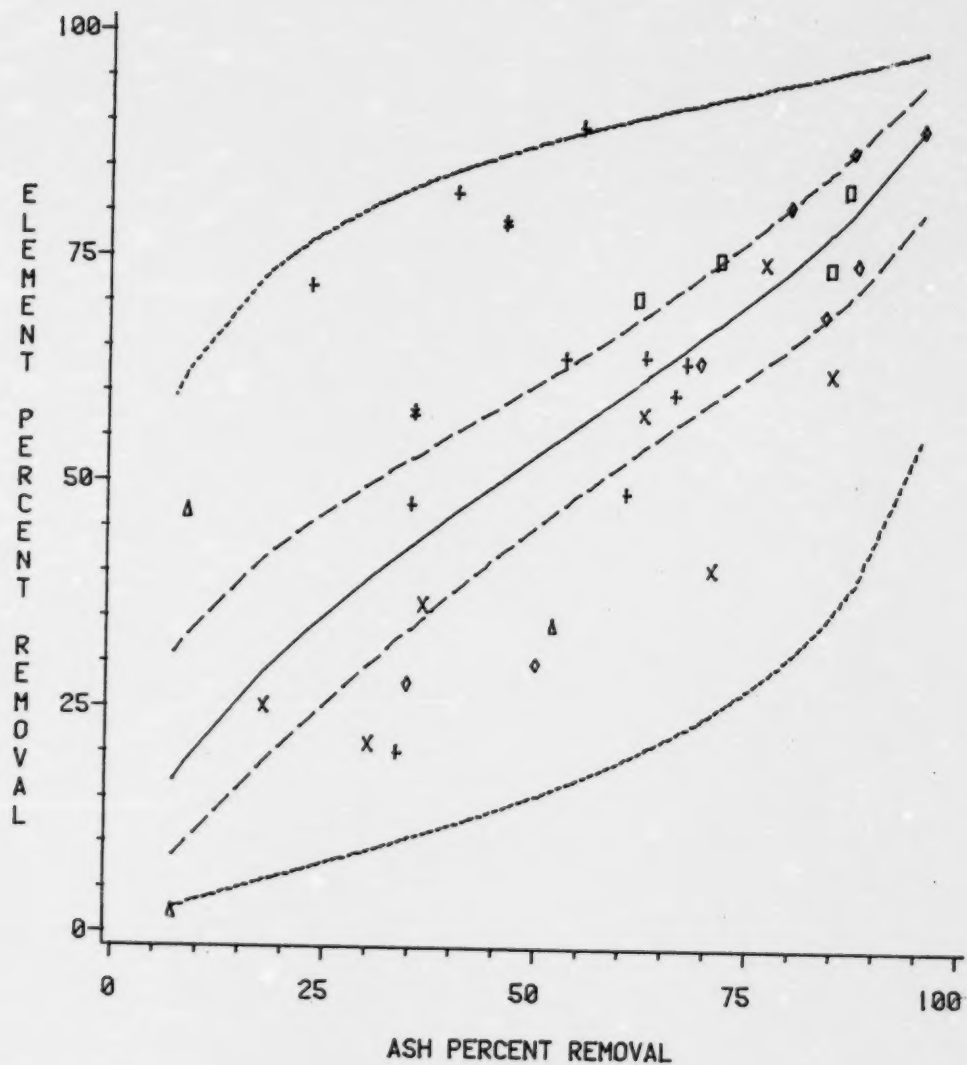
Regression Curve for Removal of Chromium as a Function of Ash Removal

ELEMENT=CU



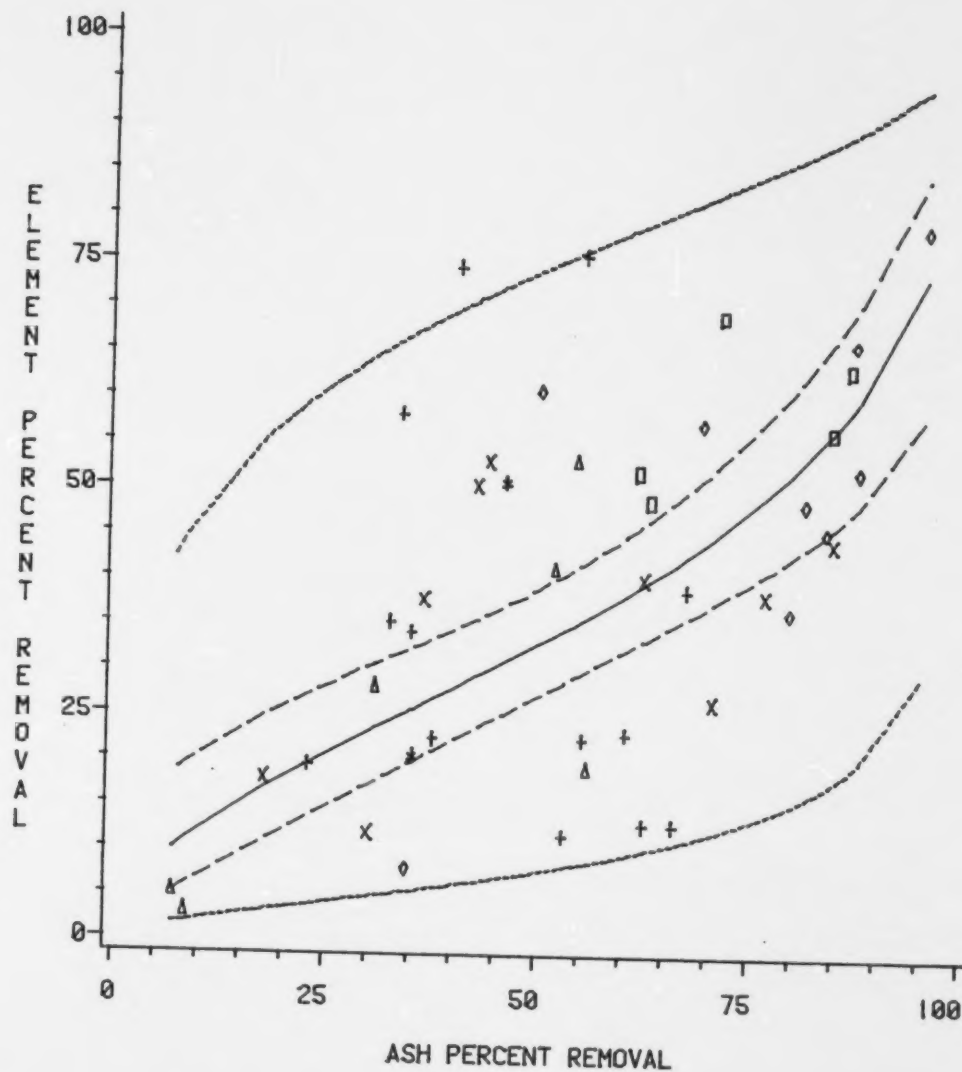
Regression Curve for Removal of Copper as a
Function of Ash Removal

ELEMENT=FE

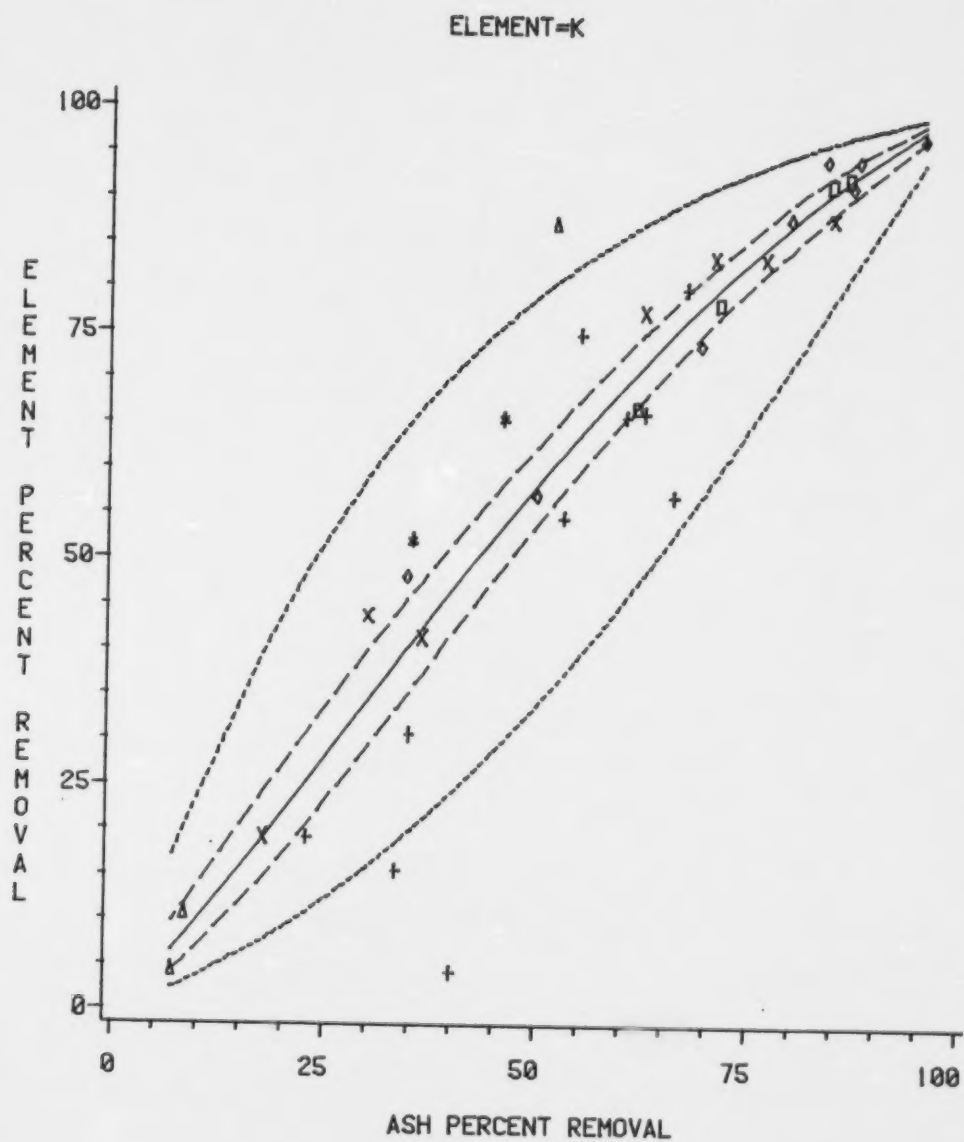


Regression Curve for Removal of Iron as a
Function of Ash Removal

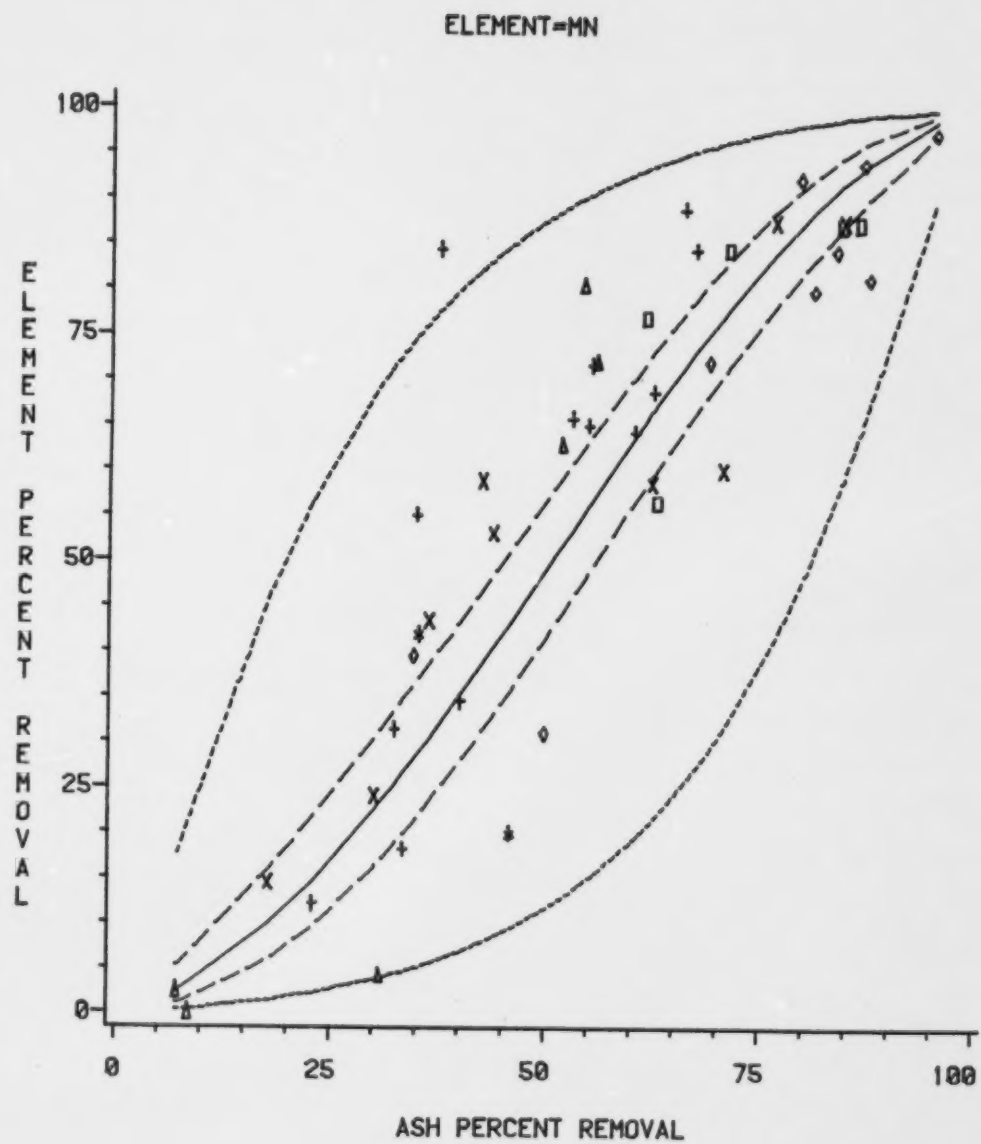
ELEMENT=HG



Regression Curve for Removal of Mercury as a Function of Ash Removal

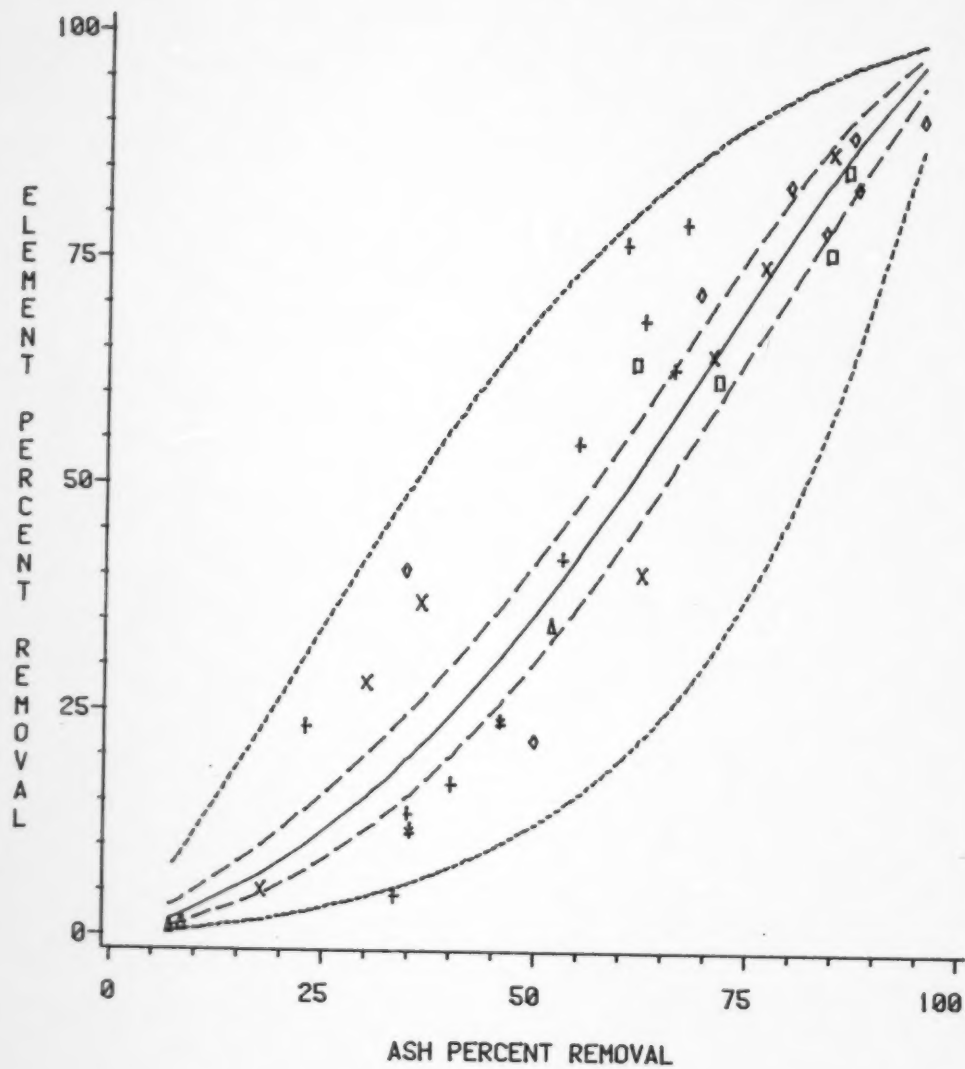


Regression Curve for Removal of Potassium as a
Function of Ash Removal



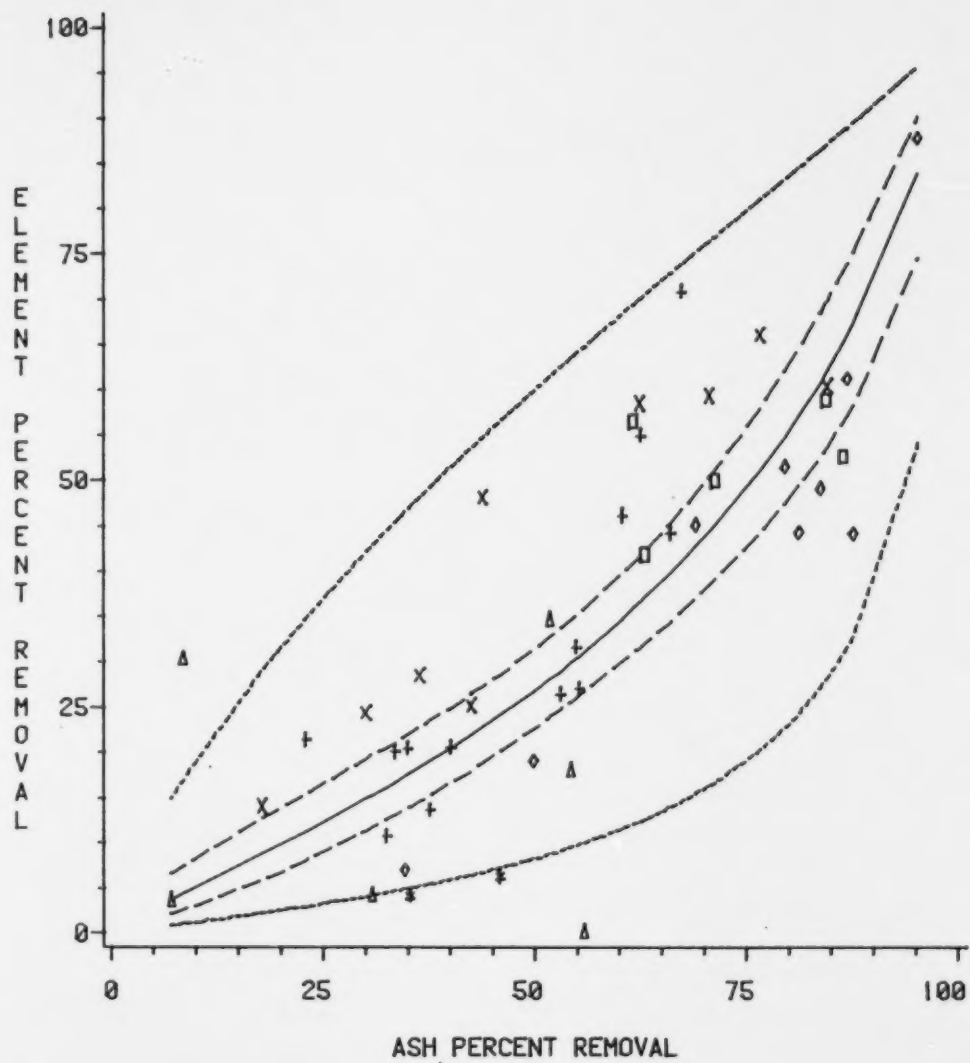
Regression Curve for Removal of Manganese as a
Function of Ash Removal

ELEMENT=NA

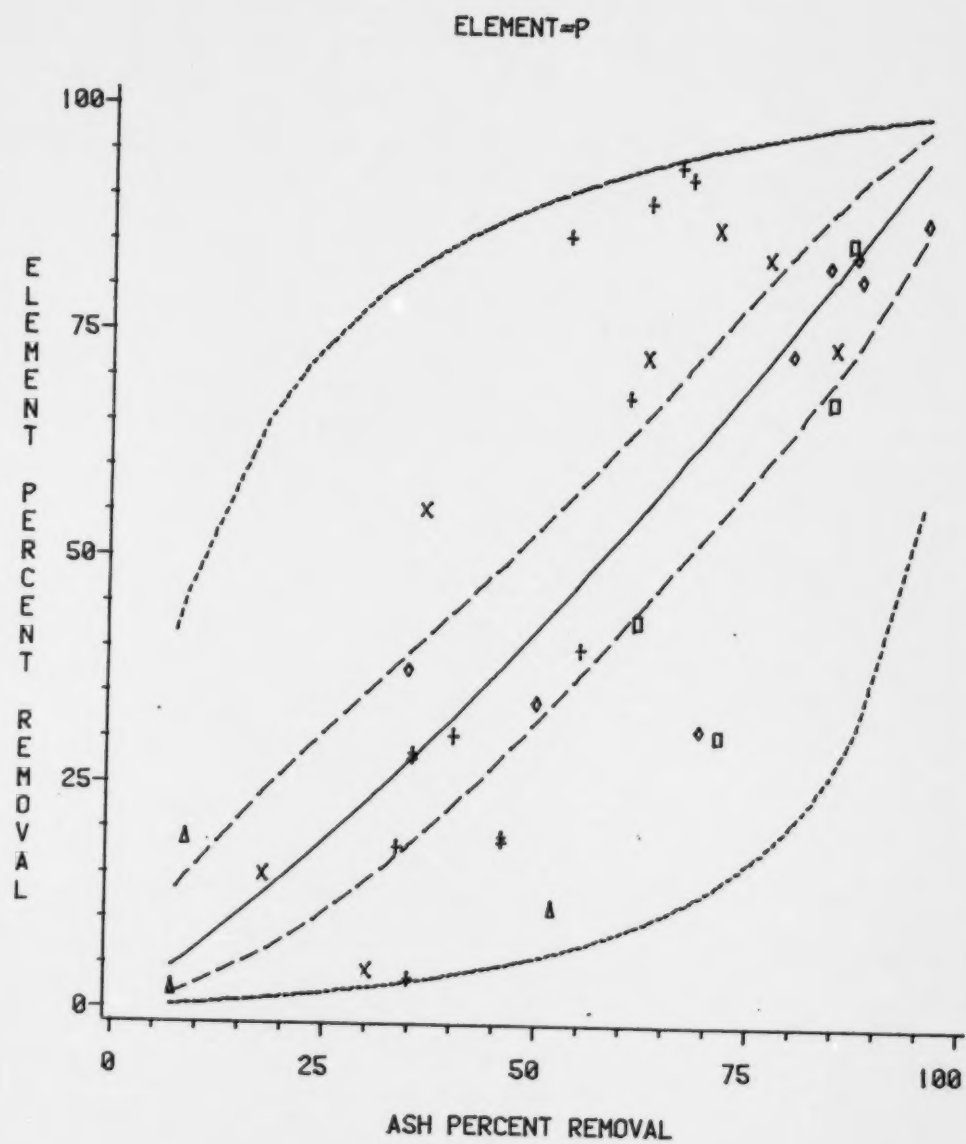


Regression Curve for Removal of Sodium as a
Function of Ash Removal

ELEMENT=NI

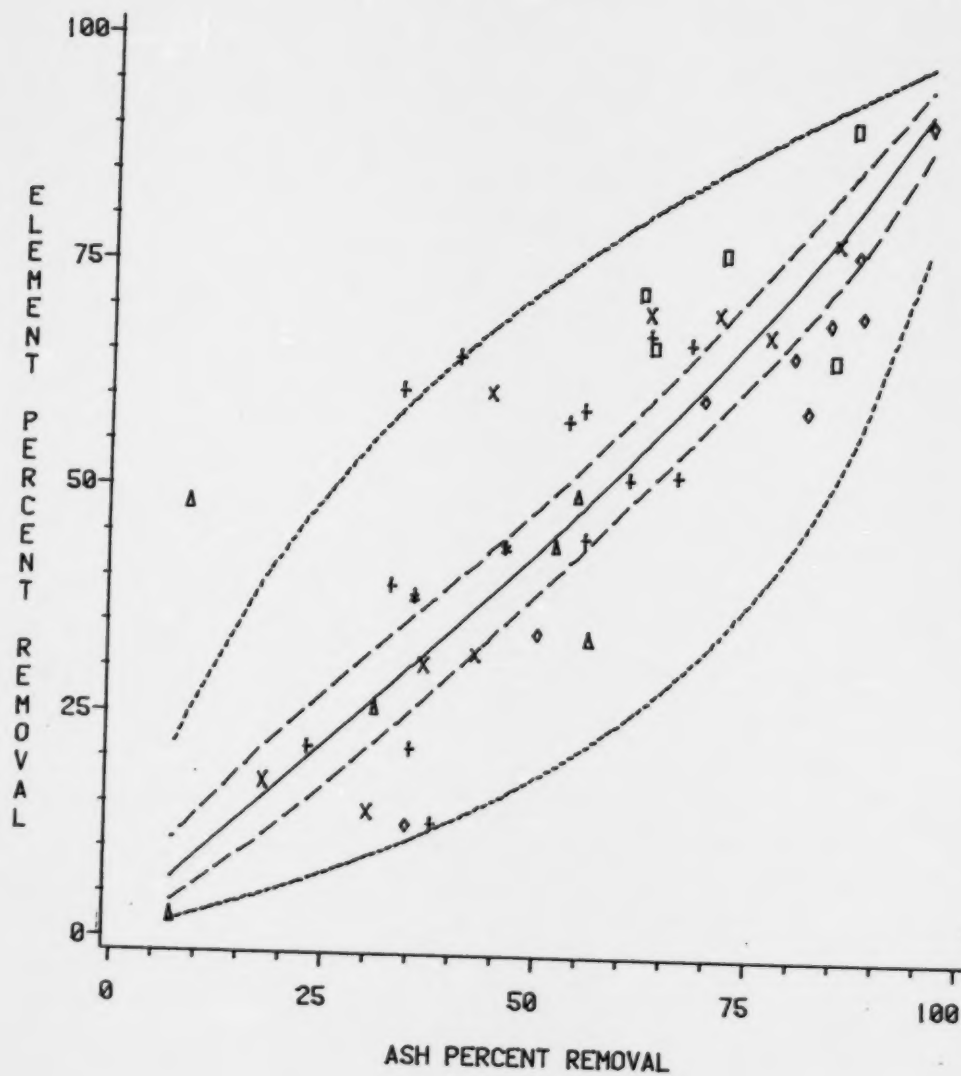


Regression Curve for Removal of Nickel as a
Function of Ash Removal



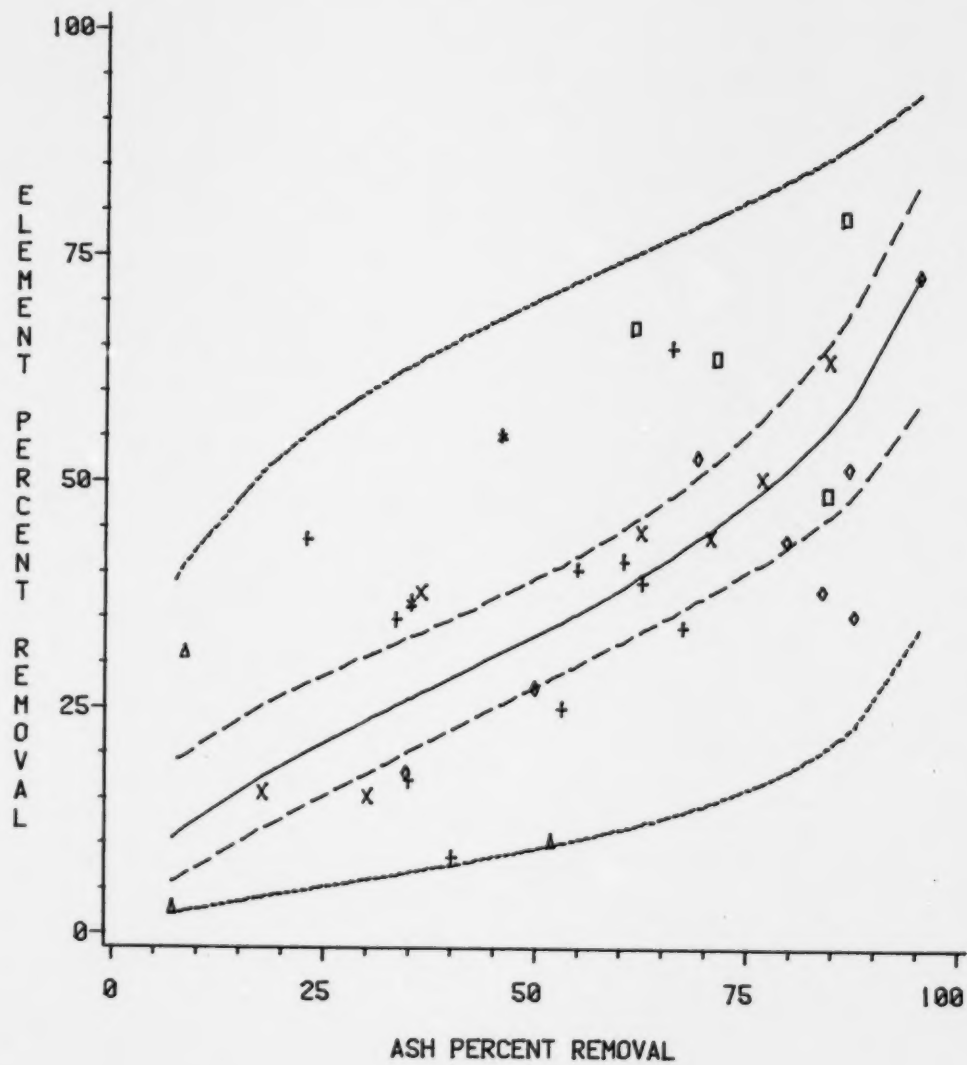
Regression Curve for Removal of Phosphorus as a
Function of Ash Removal

ELEMENT=PB



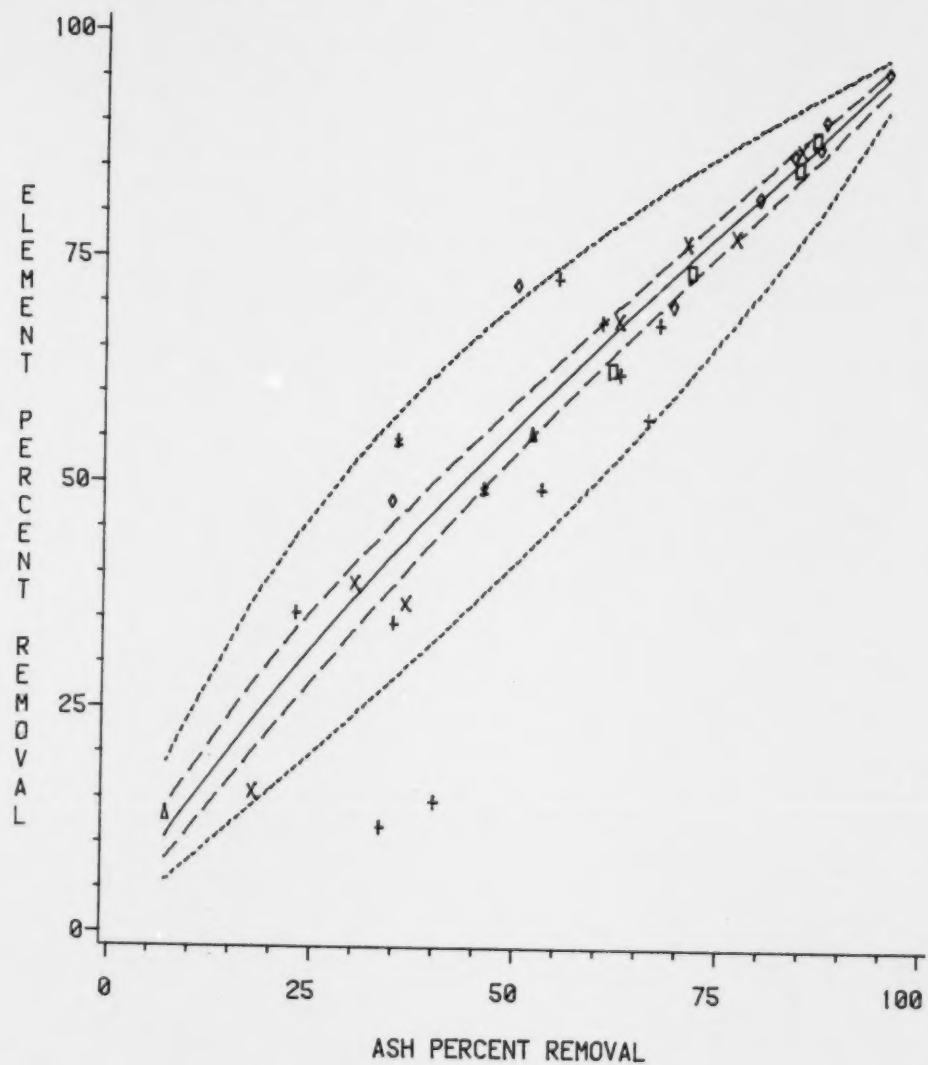
Regression Curve for Removal of Lead as a
Function of Ash Removal

ELEMENT=SE

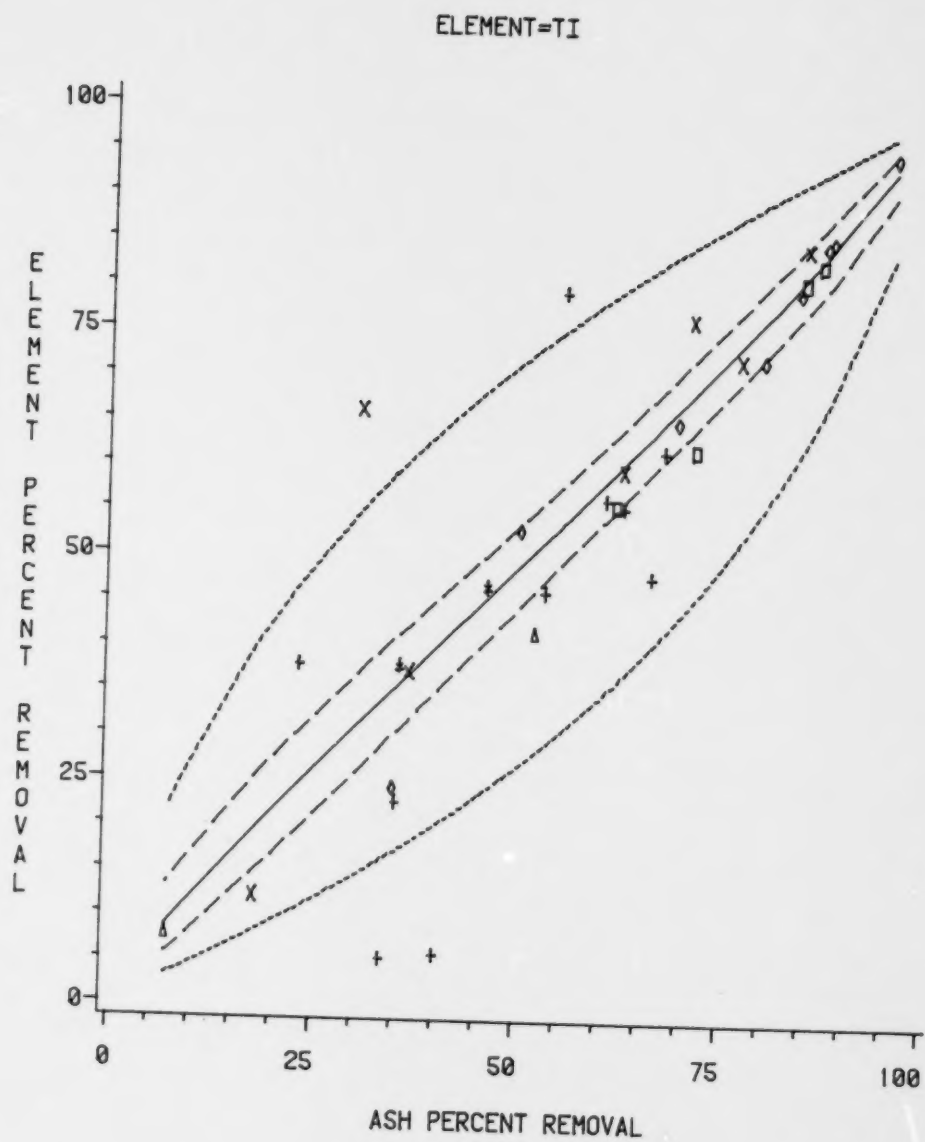


Regression Curve for Removal of Selenium as a
Function of Ash Removal

ELEMENT=SI

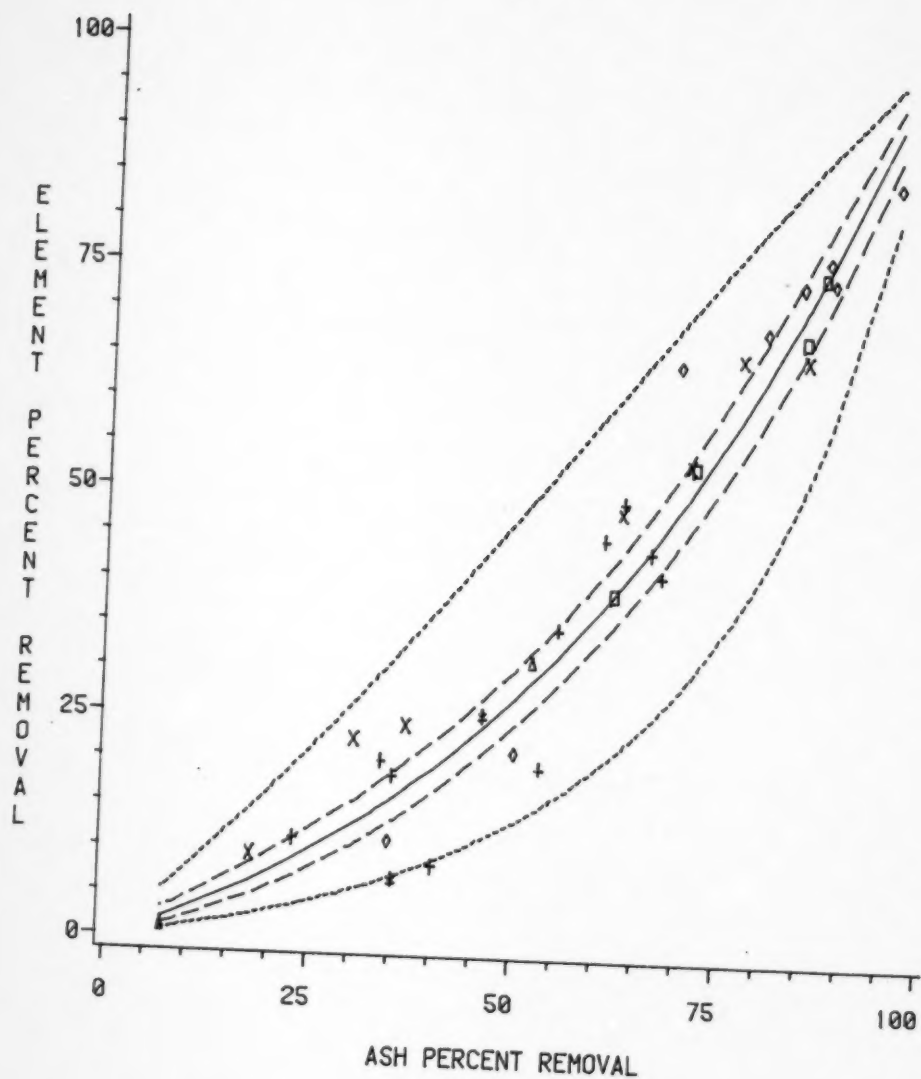


Regression Curve for Removal of Silicon as a Function of Ash Removal



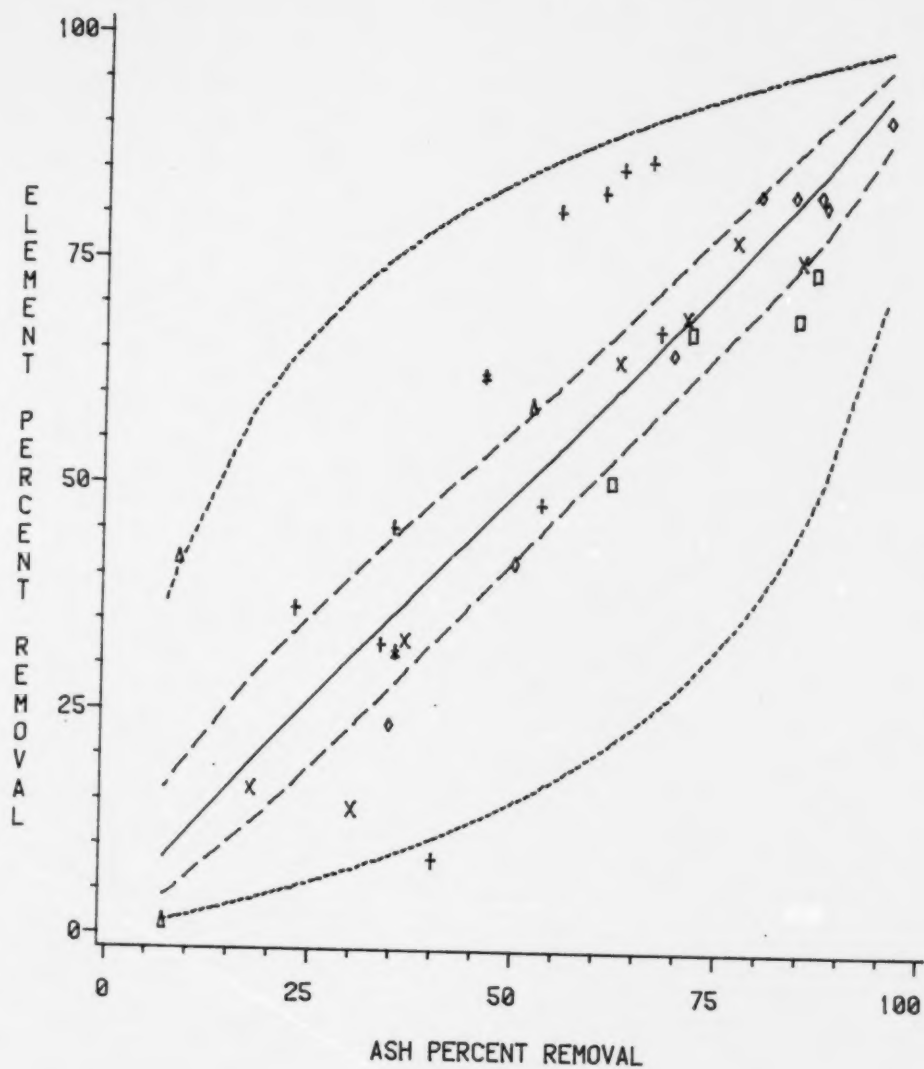
Regression Curve for Removal of Titanium as a
Function of Ash Removal

ELEMENT=V



Regression Curve for Removal of Vanadium as a
Function of Ash Removal

ELEMENT=ZN



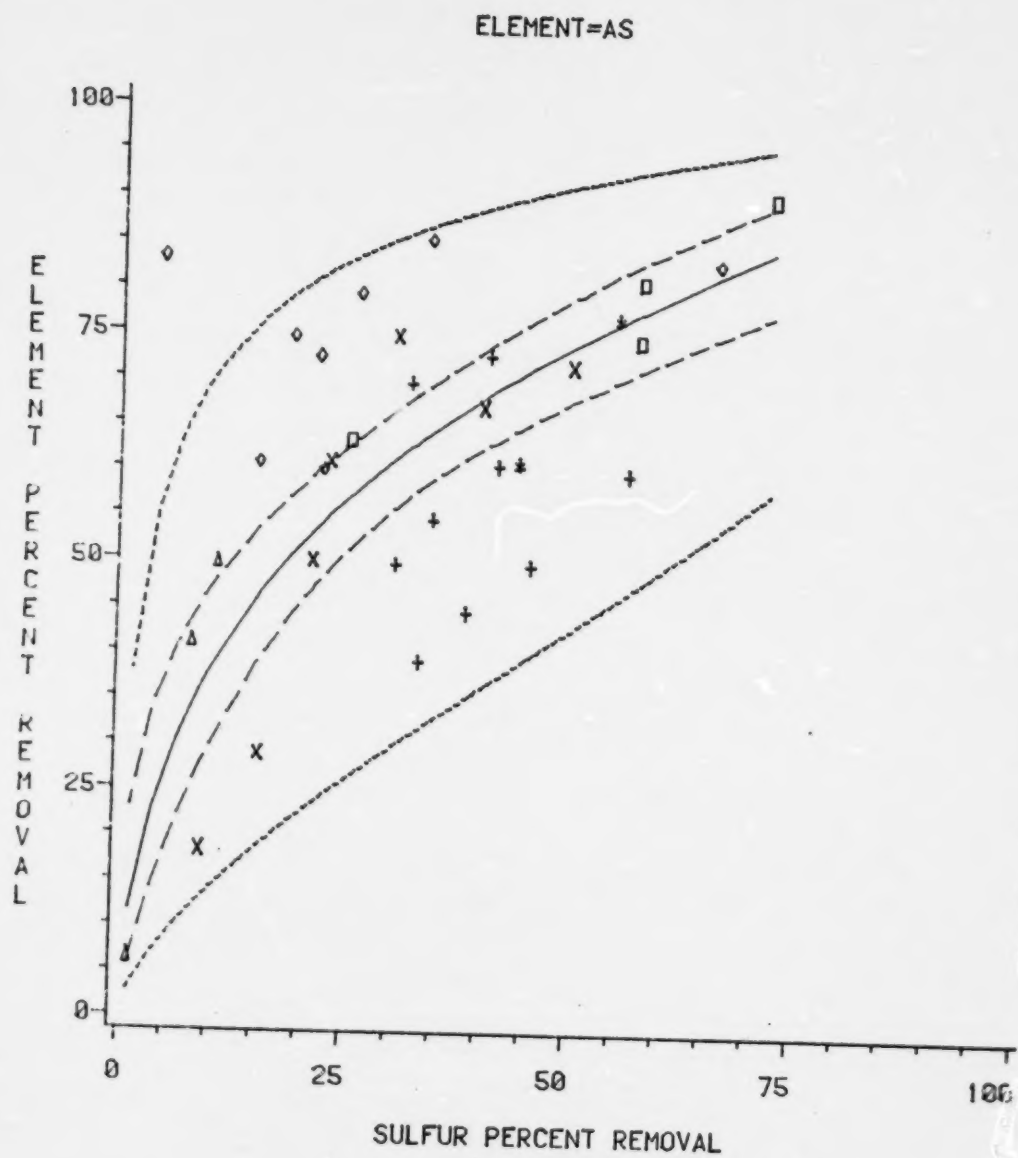
Regression Curve for Removal of Zinc as a
Function of Ash Removal

SECTION III-2

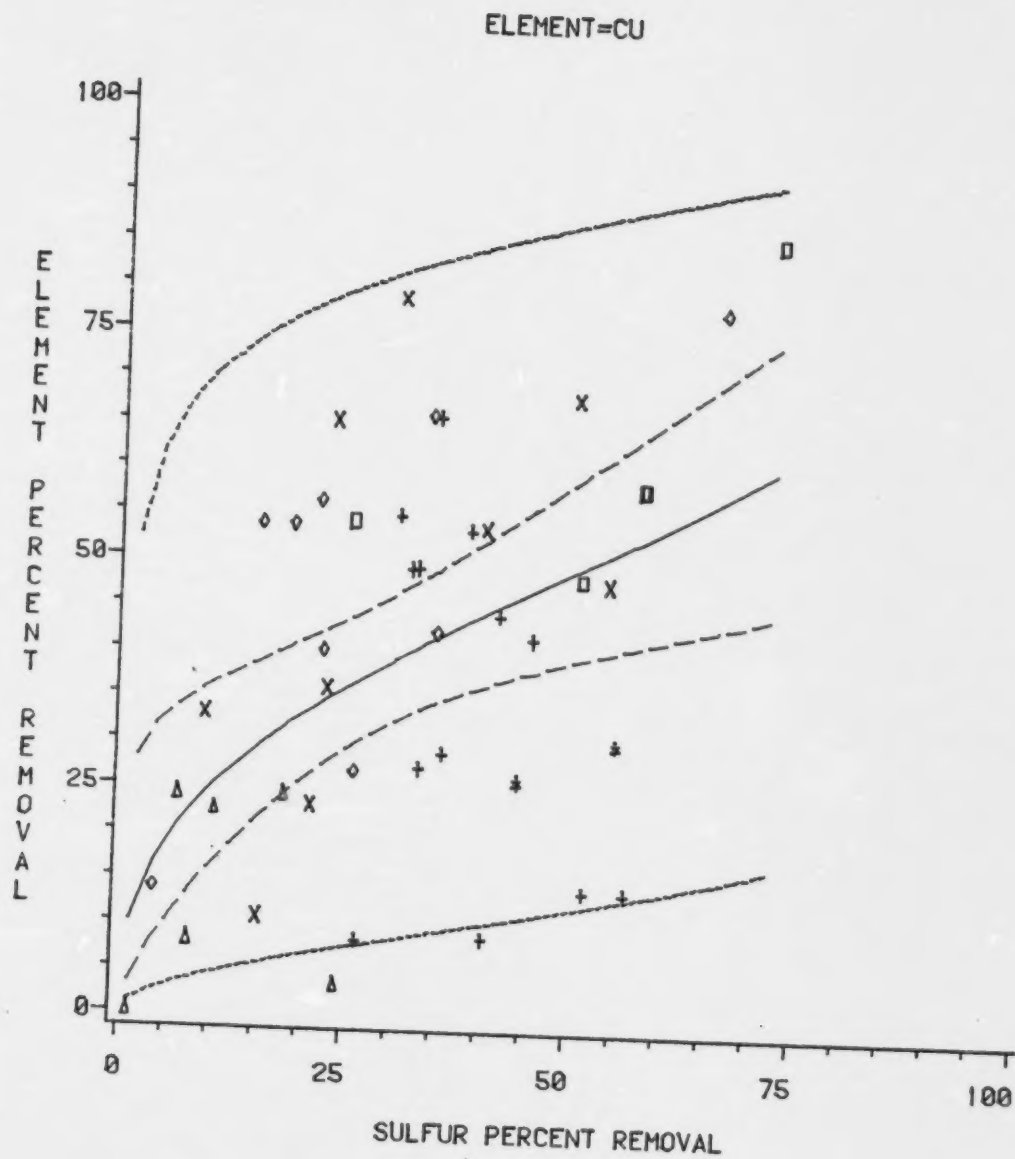
VERSUS SULFUR

+ INTERIOR
* N GRT PLAIN
x AP MONON
◻ AP ALLEG
◊ AP POTTSVILLE
Δ ROCKY MTN

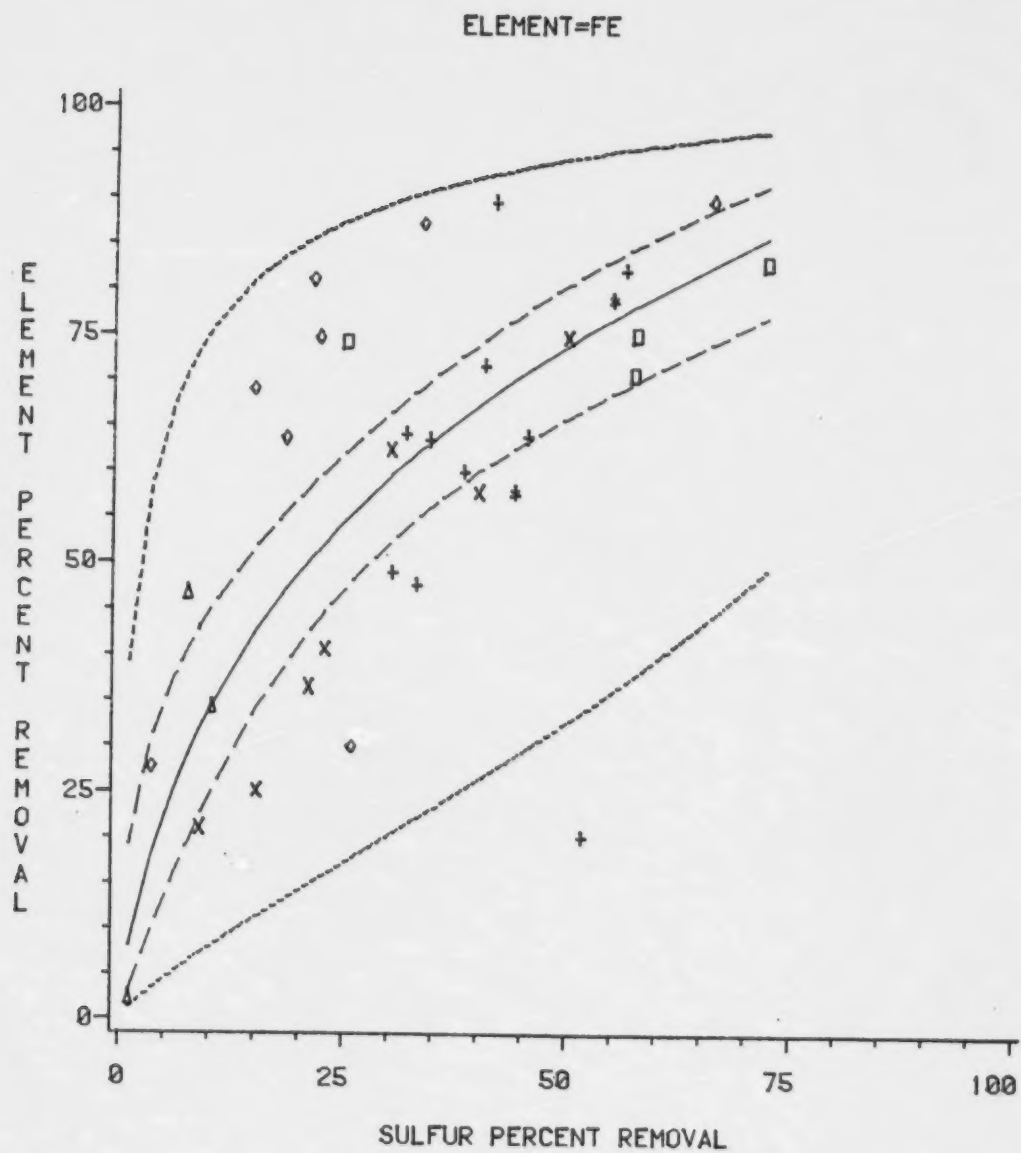
—— MEAN LINE
---- 95% CI MEAN
.... 95% CI INDIVIDUAL



Regression Curve for Removal of Arsenic as a
Function of Sulfur Removal

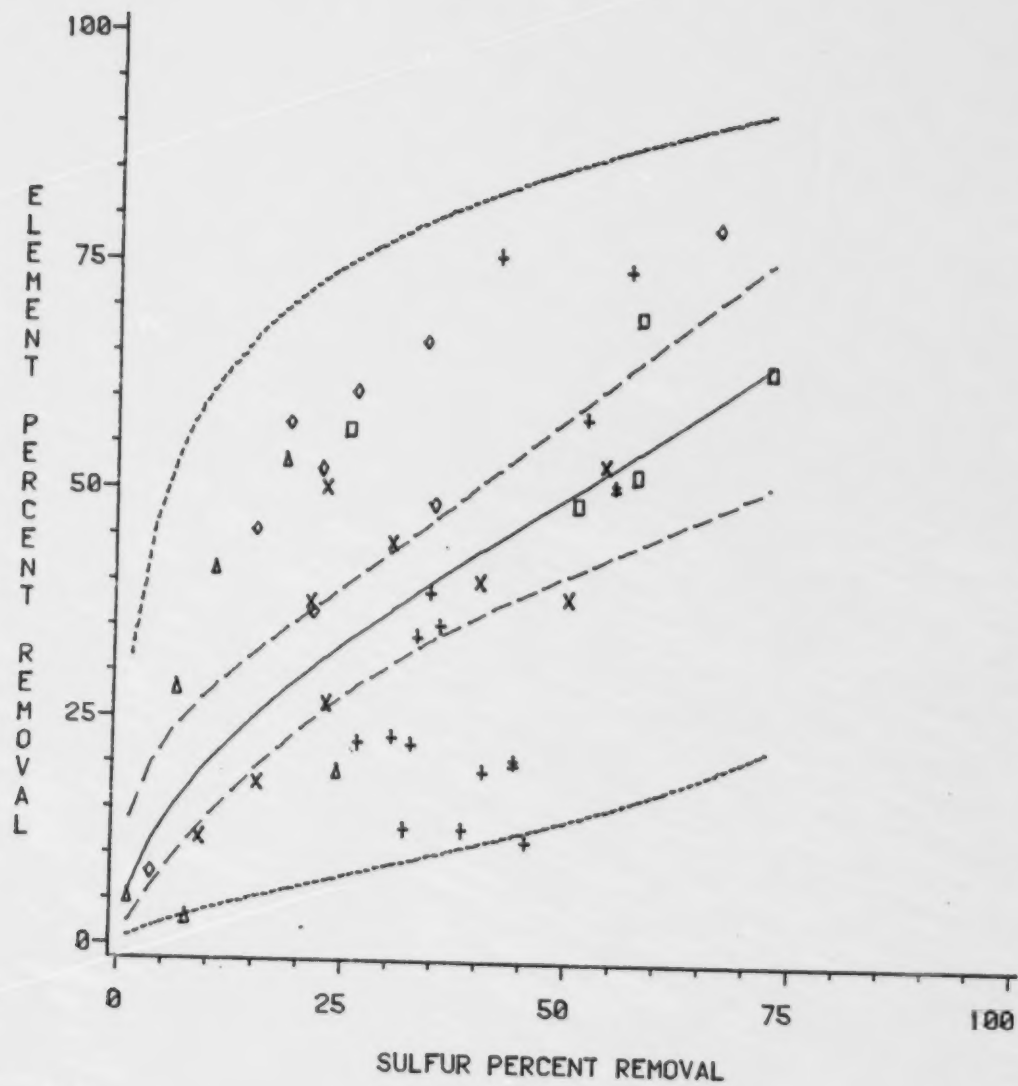


Regression Curve for Removal of Copper as a
Function of Sulfur Removal



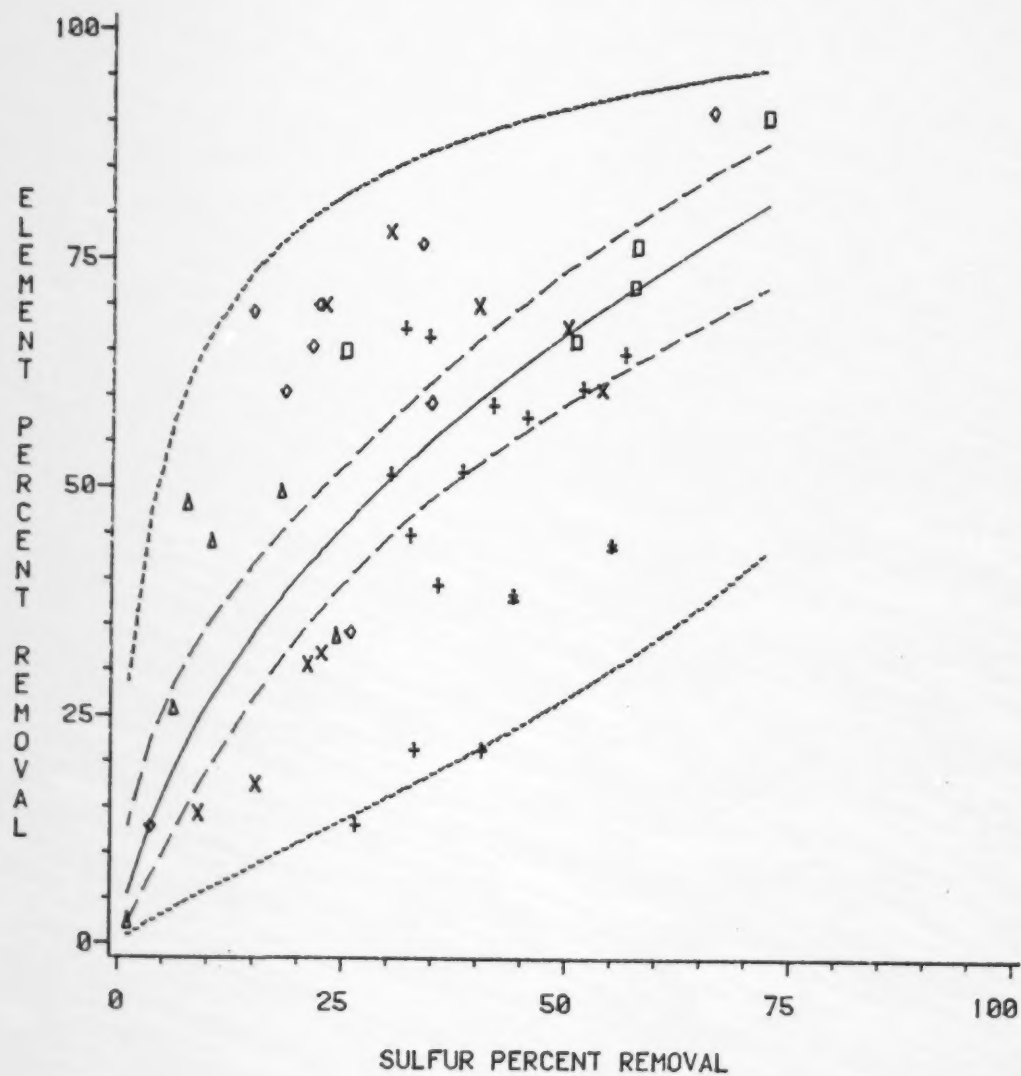
Regression Curve for Removal of Iron as a
Function of Sulfur Removal

ELEMENT=HG

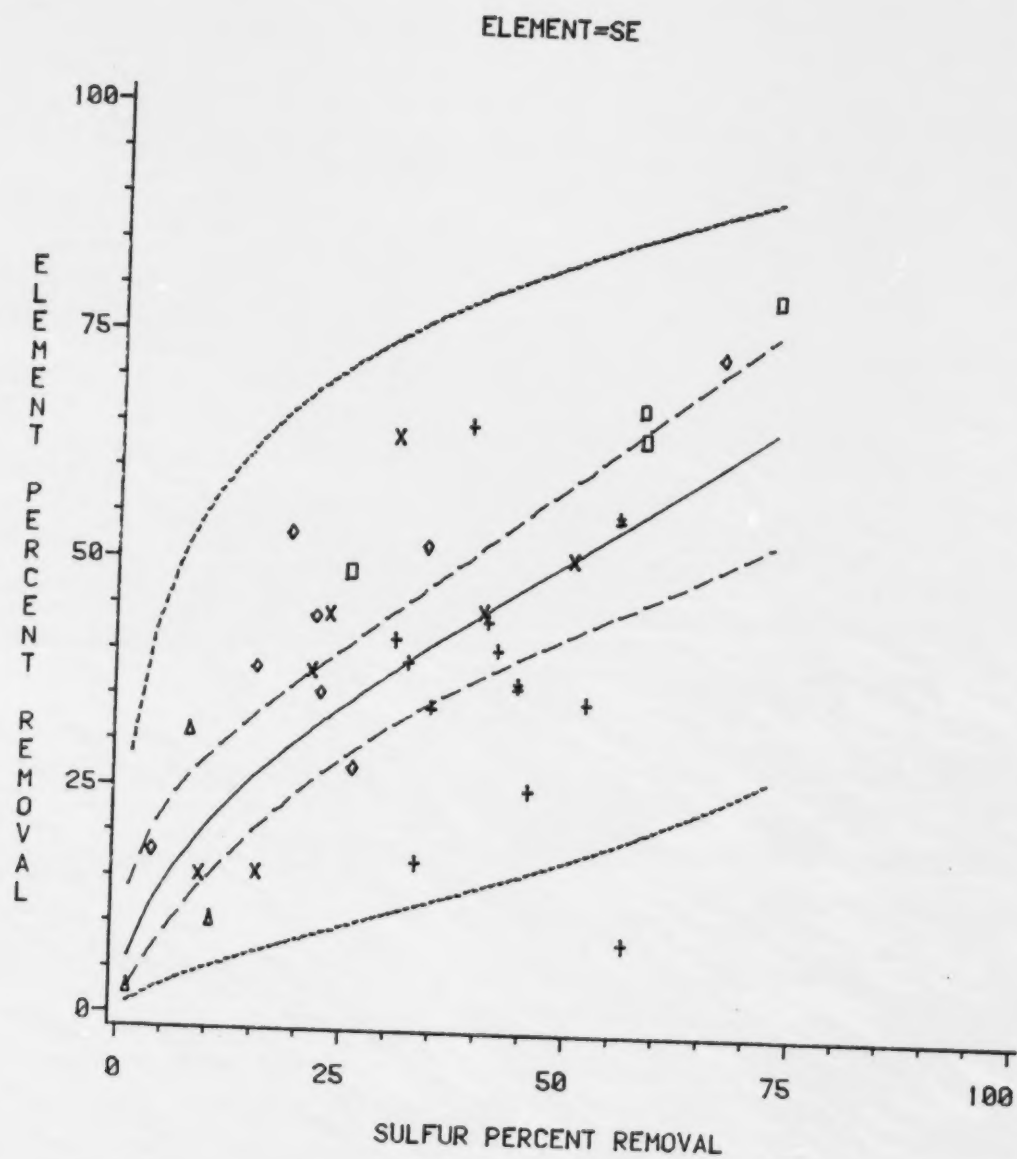


Regression Curve for Removal of Mercury as a Function of Sulfur Removal

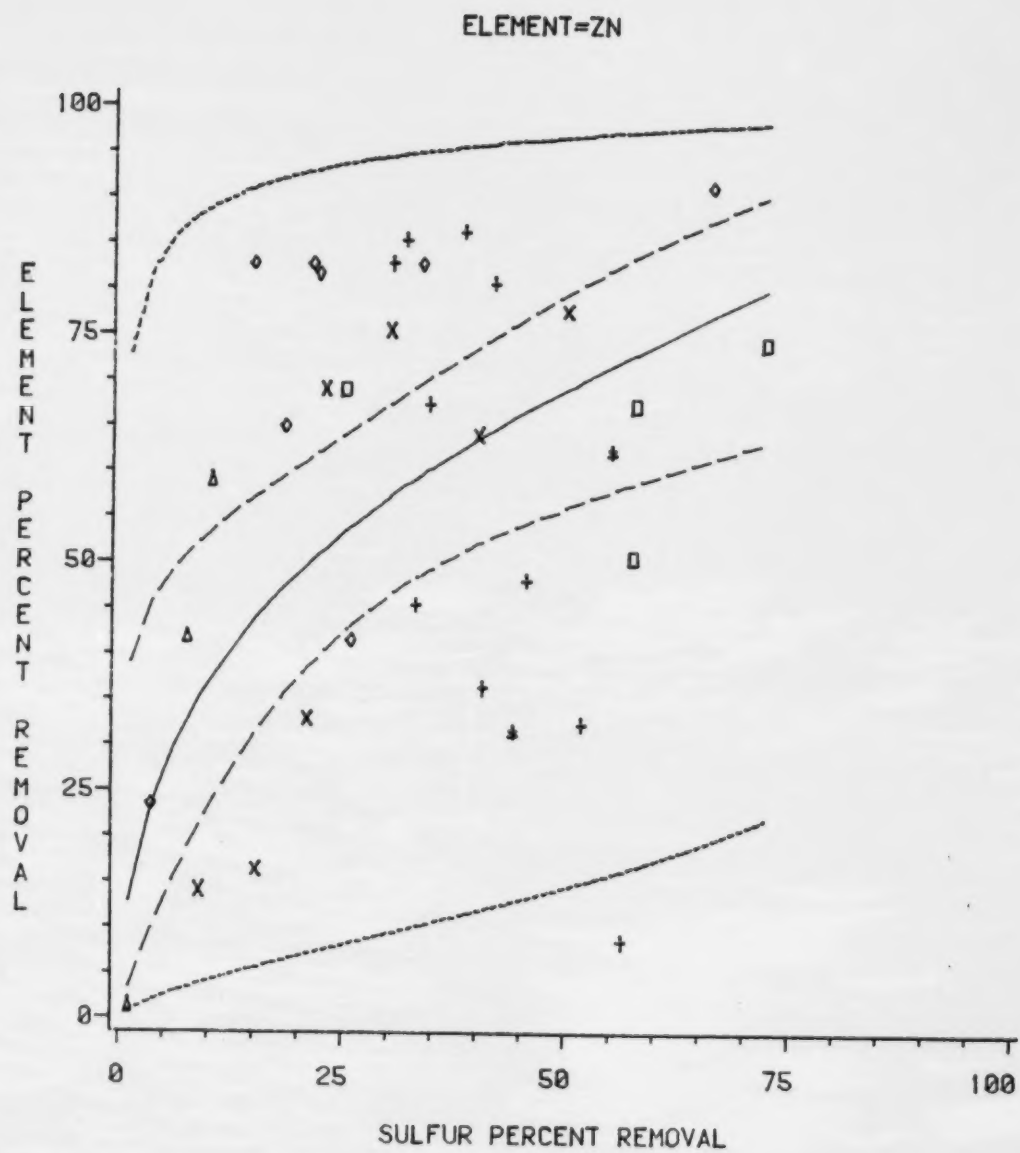
ELEMENT=PB



Regression Curve for Removal of Lead as a
Function of Sulfur Removal



Regression Curve for Removal of Selenium as a
Function of Sulfur Removal



Regression Curve for Removal of Zinc as a
Function of Sulfur Removal

APPENDIX IV
REGIONAL AVERAGES OF TRACE ELEMENT REMOVAL
VERSUS SULFUR AND ASH REMOVAL

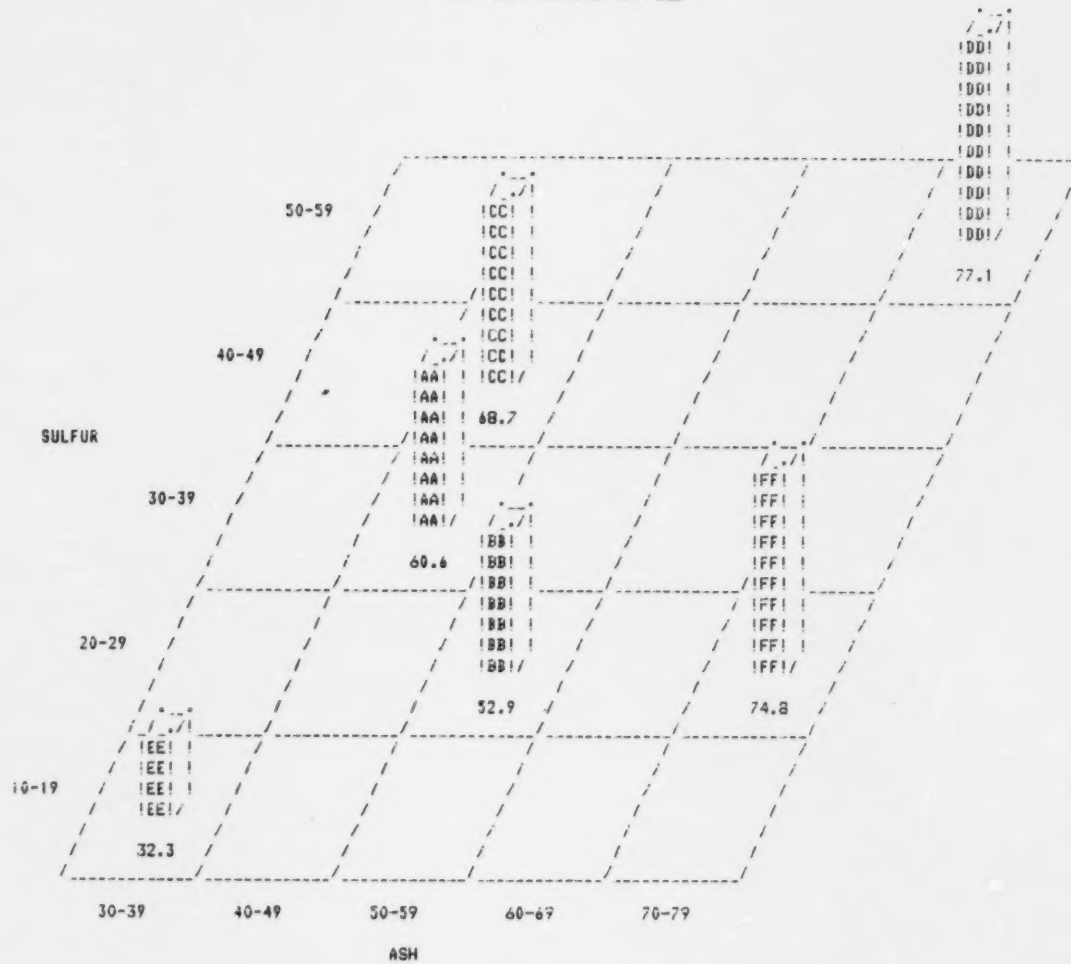
SYMBOL REGION

A = Interior
B = Ap-Alleg

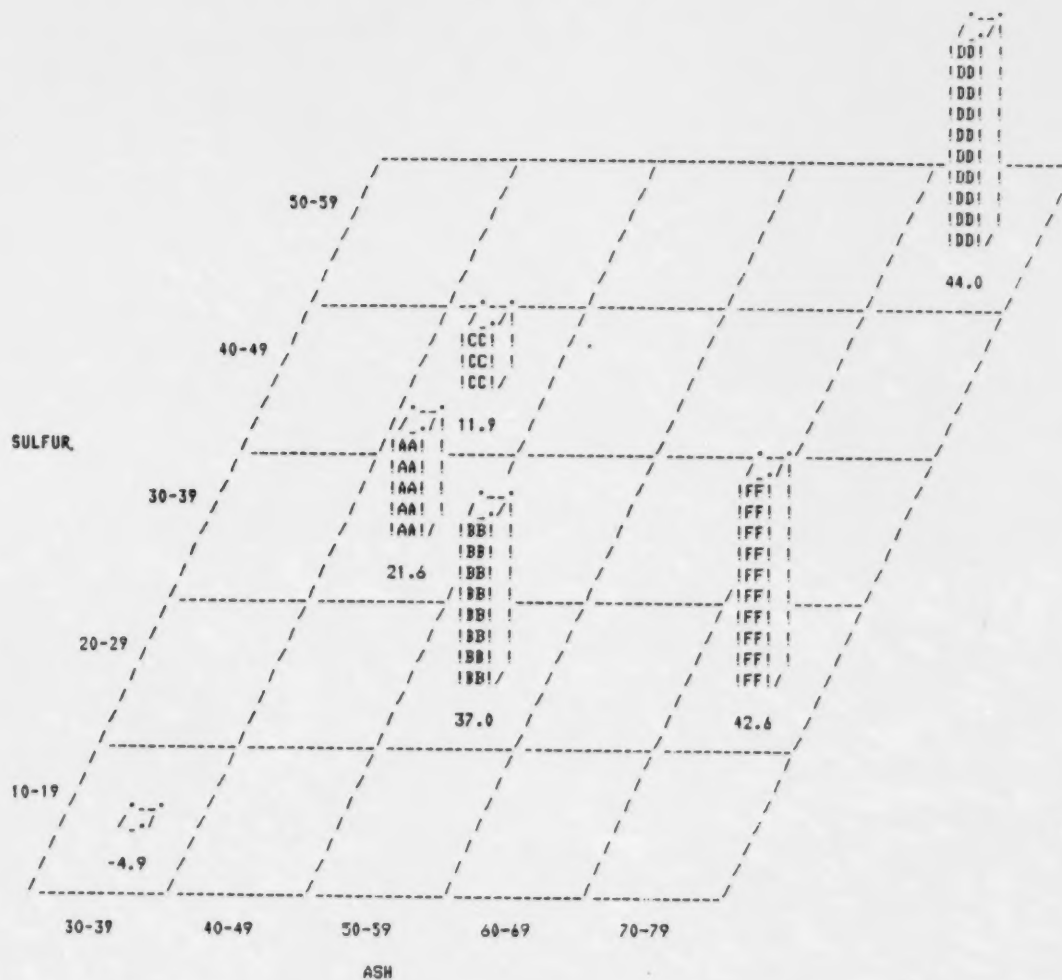
C = N Grt Plains
D = Ap-Monon

E = Rocky Mtn
F = Ap-Pottsville

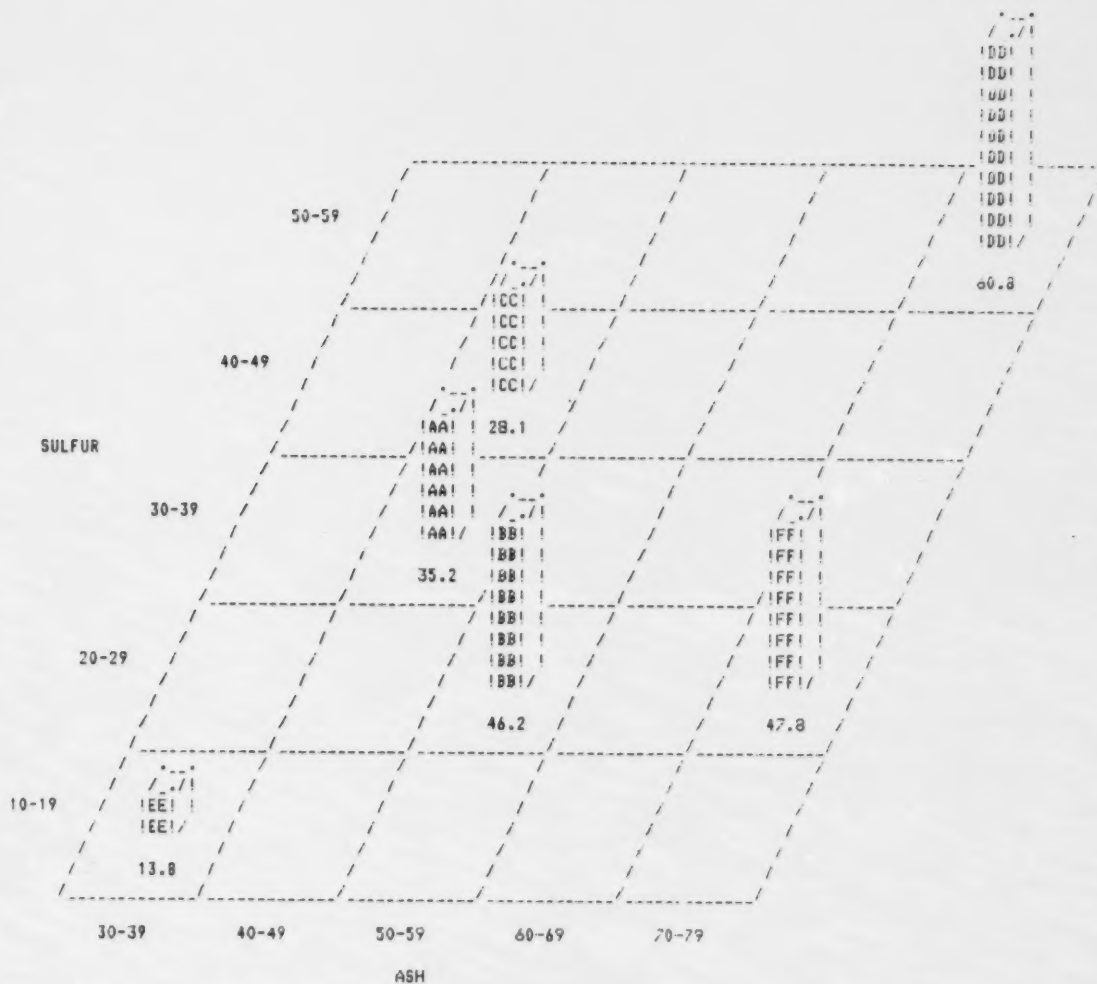
BLOCK CHART OF AS



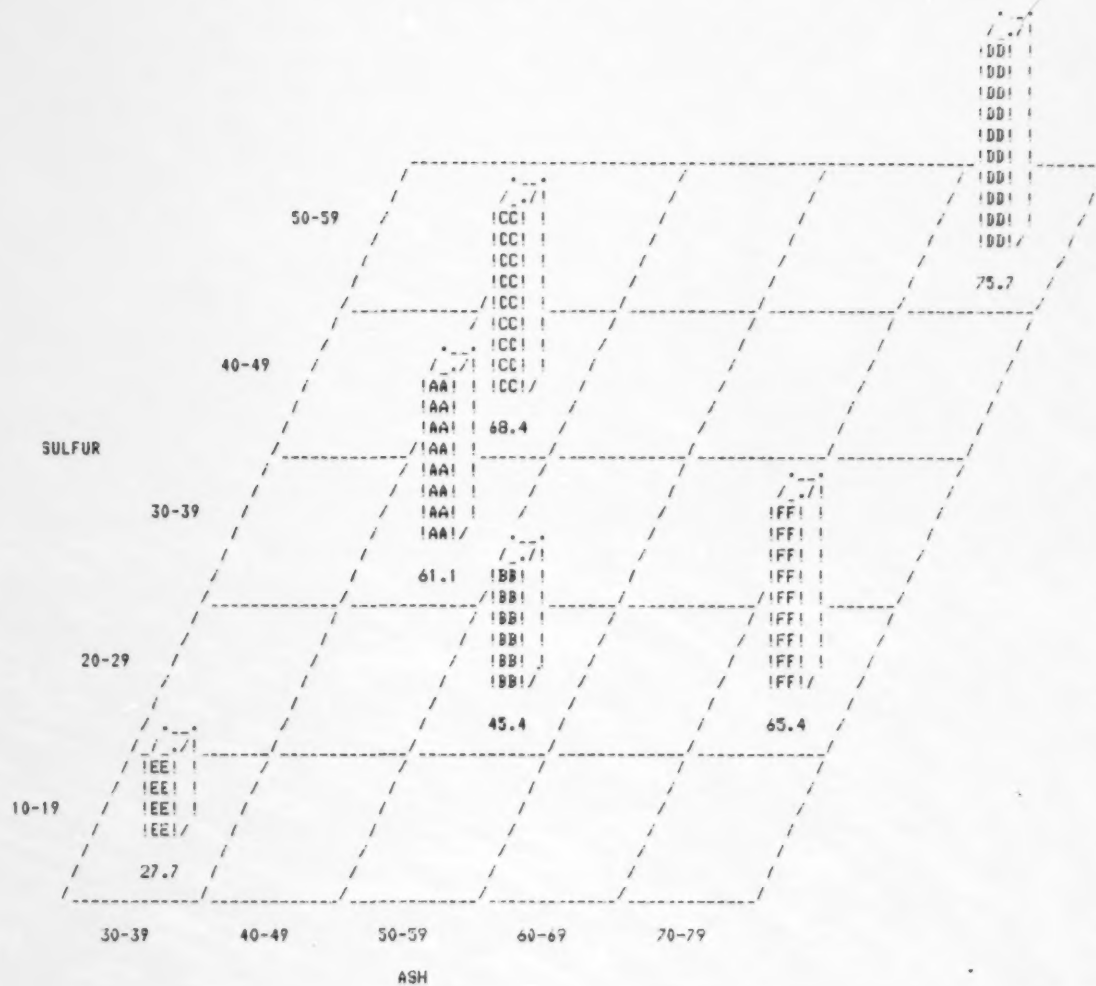
BLOCK CHART OF BE



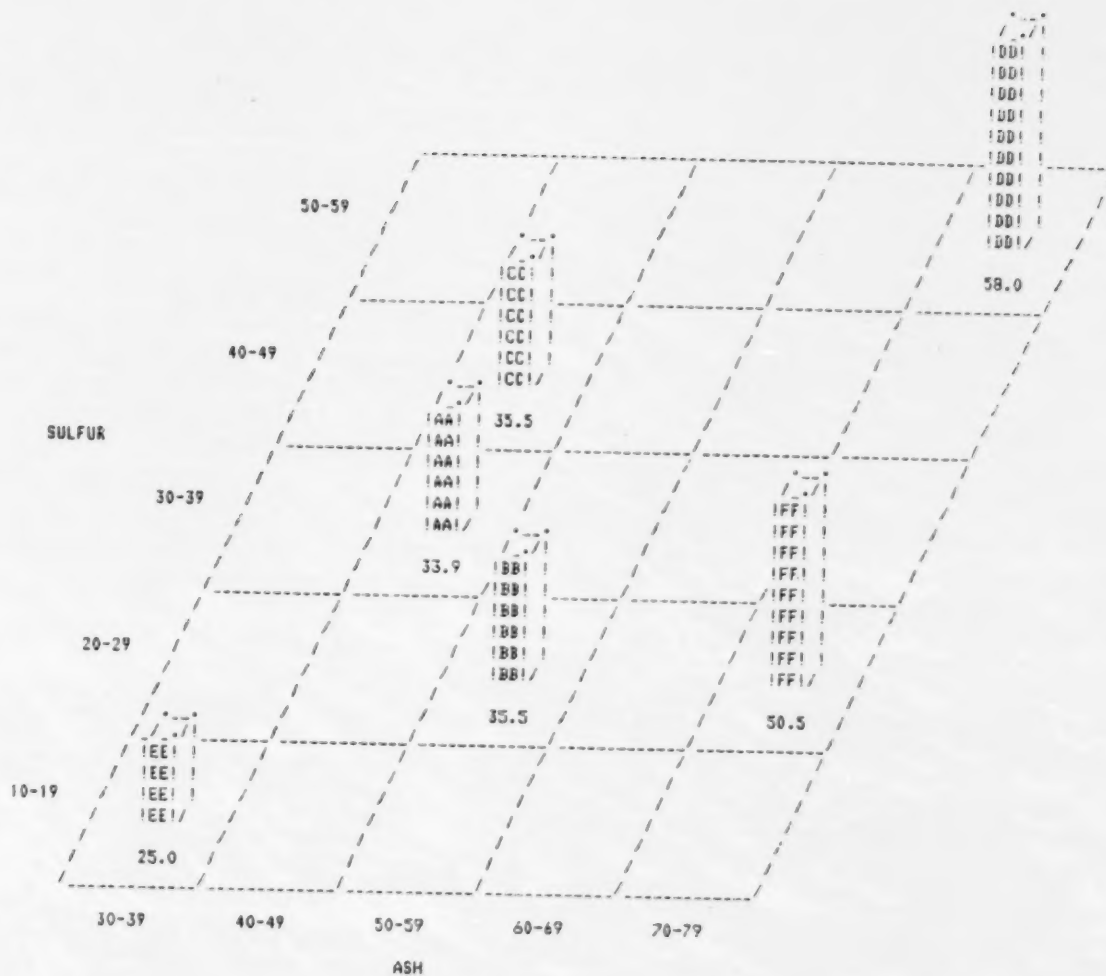
BLOCK CHART OF CU



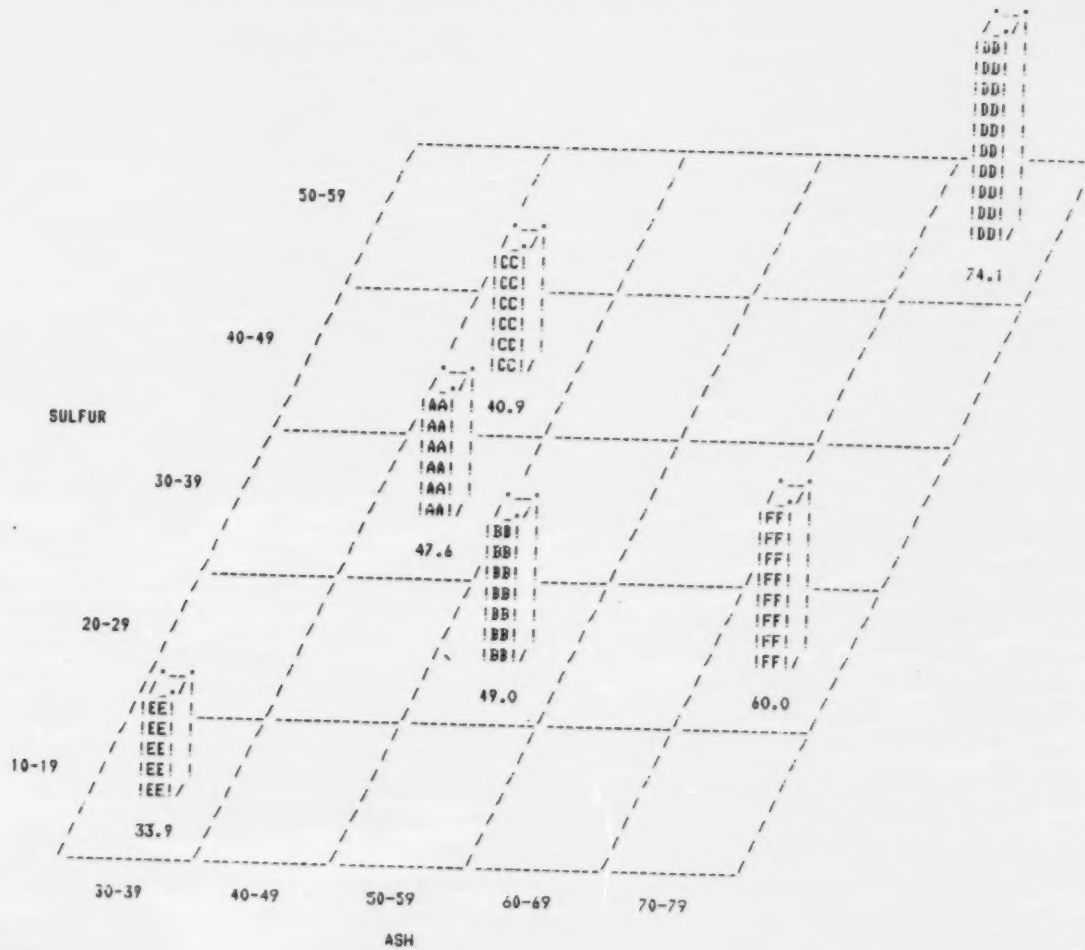
BLOCK CHART OF FE



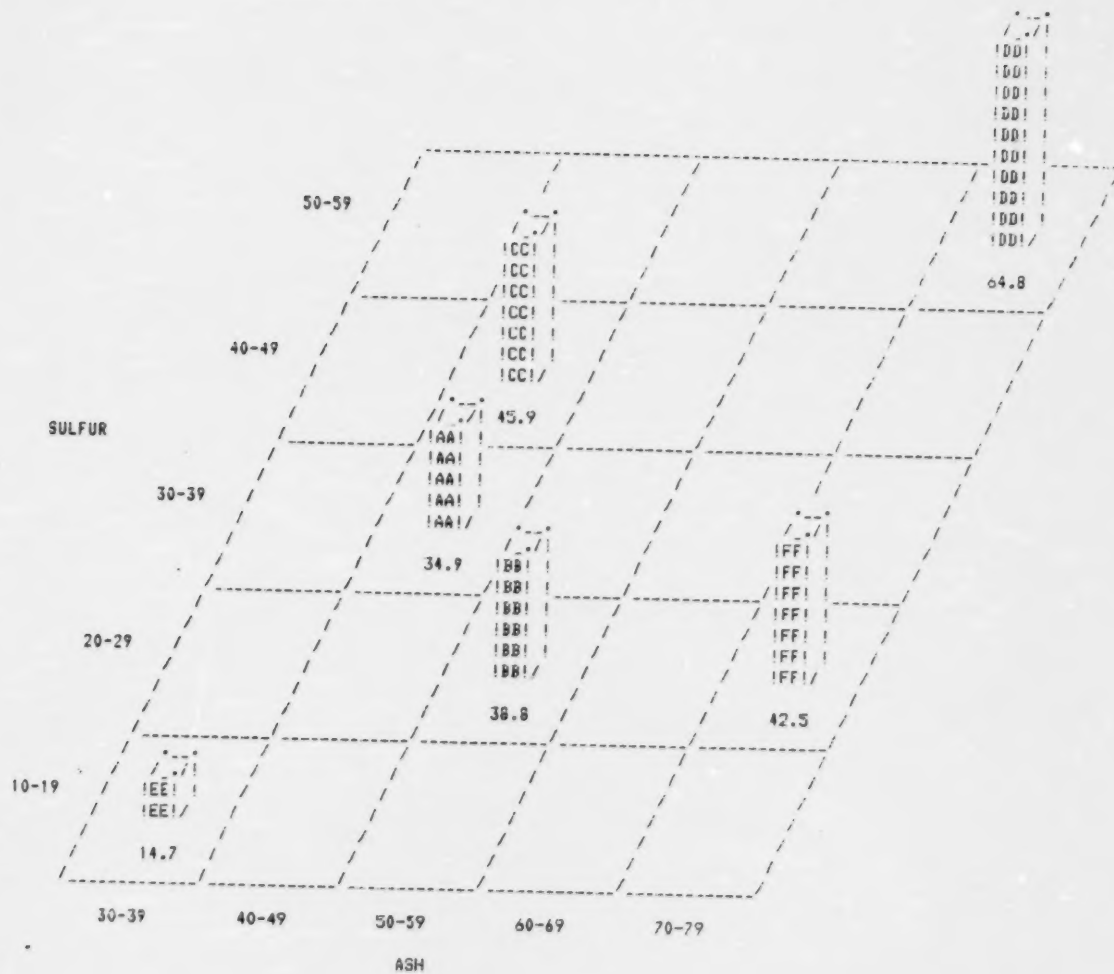
BLOCK CHART OF HQ



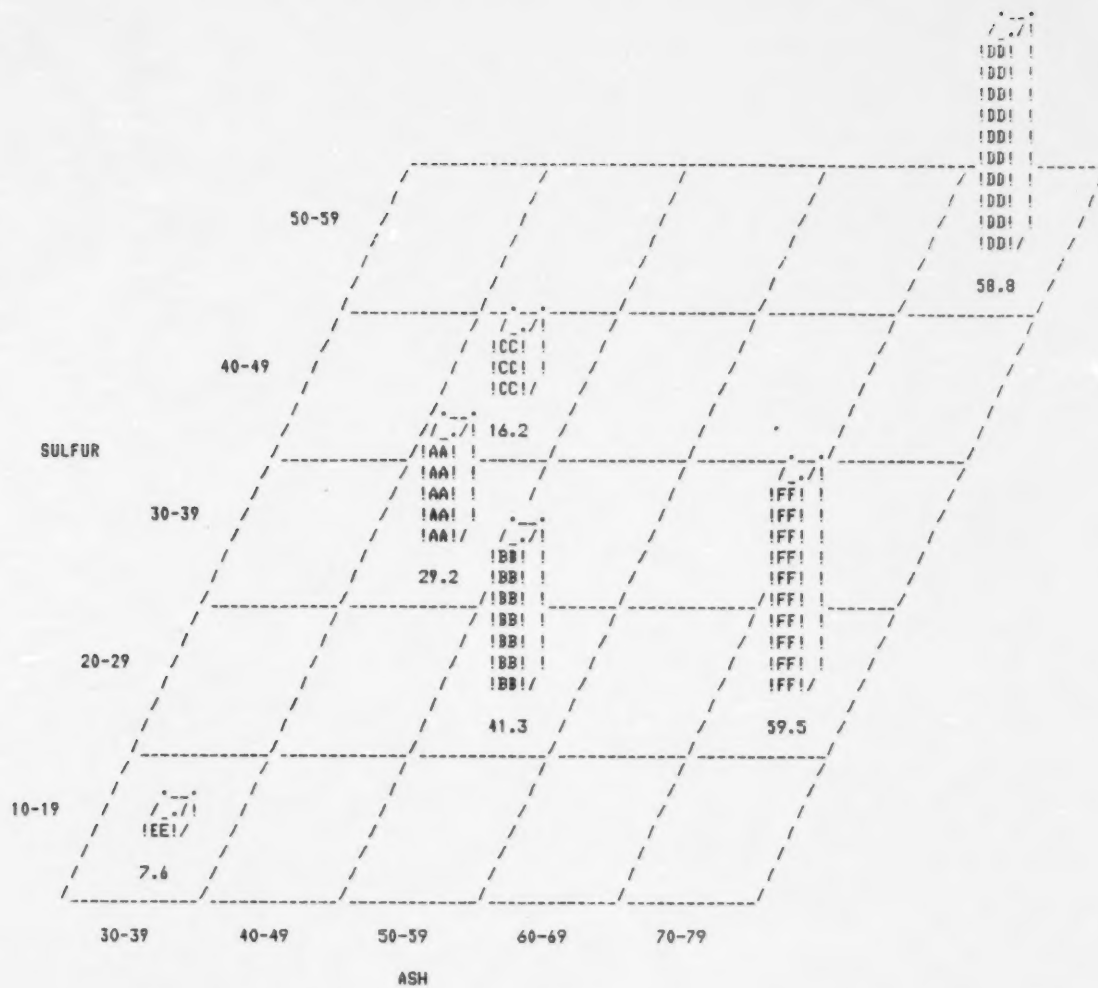
BLOCK CHART OF PB



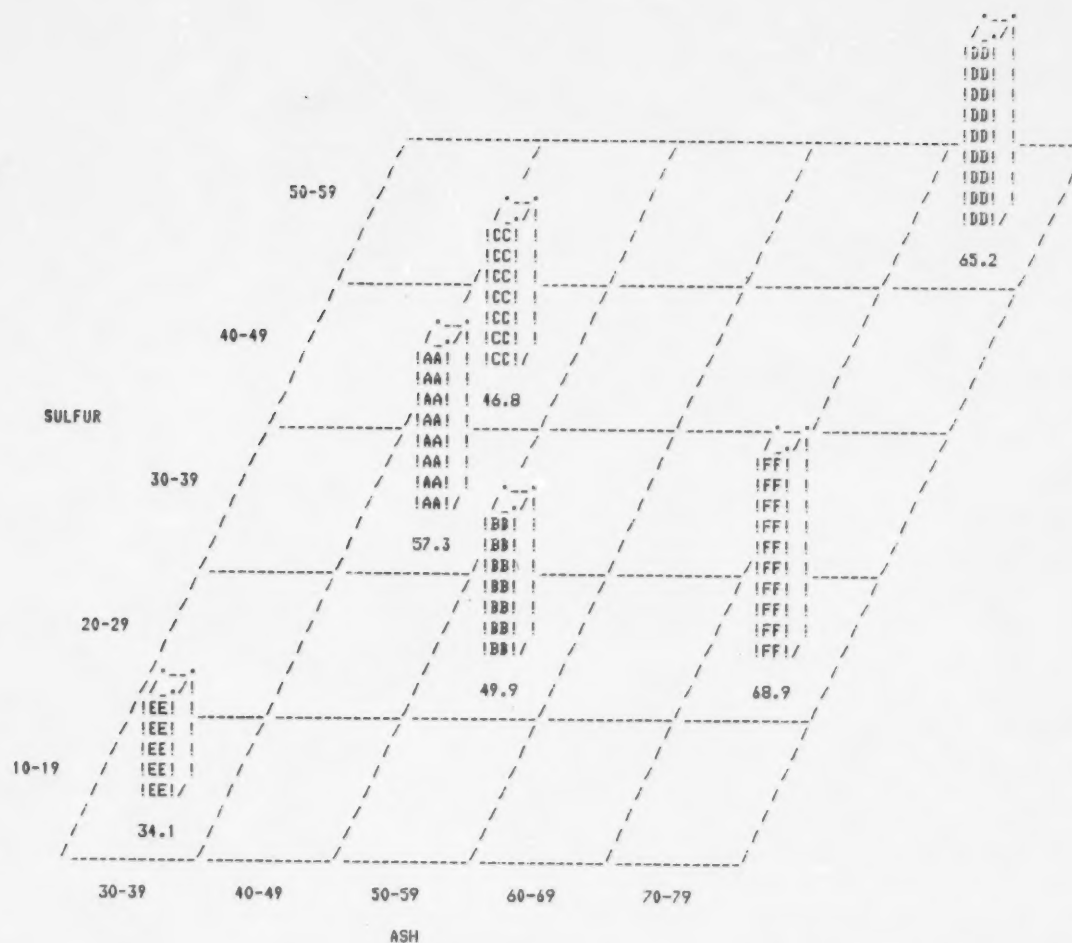
BLOCK CHART OF SE



BLOCK CHART OF V



BLOCK CHART OF ZN



APPENDIX V
ELEMENTAL DISTRIBUTION, ENRICHMENT, AND
CLOSURE DATA FOR 15 DATA SETS FROM
COAL COMBUSTION

APPENDIX V

ELEMENTAL DISTRIBUTION, ENRICHMENT, AND

CLOSURE DATA FOR 15 DATA SETS FROM COAL COMBUSTION

In this project, 15 data sets were identified which gave trace element partitioning, mass flow, and closure data from coal-fired boilers. Since closure provides a good indication of the quality of the data, only such studies were used. The data are first presented by data set for the major and the more common trace elements. All values are given in ppm, except closure values which are in percent. 100 percent would mean the same mass came out of the system that was put into it. Distribution factors have been normalized to 100 percent by dividing the measured flows in percent by the closure percentages divided by 100. A dot means no data were given.

Information about the plant, coal, authors, and date of study is given at the top of each data set. The sources of these data correspond to the references for Section 4 according to the following matrix.

<u>Study No.</u>	<u>Reference No.</u>
1,2	6
3,4,5	7
6,7	8
8	9
9	11
10	10
11	12
12	13
13	14
14	15
15	16

Of the 15 studies, four (data sets 1, 2, 5, 9) were on cyclone boilers. Because these boilers are no longer in widespread use and because their ash distribution is distinct from other systems, they have been broken into a subset by themselves. Within this subset, data set 5, which is from a plant with only a cyclone for particulate control, had very high emissions and thus tends to distort the averaged data.

The remaining 11 data sets are for pulverized coal boilers with greater than 98% particulate control. Average emission factors for each element have been calculated. Also included is the enrichment ratio in each ash category with respect to aluminum. That is, if 80 percent of the aluminum was found in the hopper ash but 90 percent of chromium was found there, the chromium would be enriched with respect to the aluminum by a ratio of $.90/.80 = 1.125$. This grouping format also compares the closures for each element; if they vary or are consistently far from 100, it is an indication that the sampling or analytical techniques are not well refined.

At the bottom of each column are given the average and standard deviation. These data have been compiled into a table which is given in Section 4 (Tables 54 and 55) of the main body of this report.

TABLE V-1

Elemental distributions in coal and ashes from 15 data sets. Closure is defined as elemental mass flow in minus elemental mass flow out all divided by elemental mass flow in and all times 100.

PLANT NAME: TA ALLEN-UNIT #2
REFERENCE NUMBER: T-1
BOTTLER TYPE: CYCLCNF, 290 MW
AUTHORS: LYON W.S.
DATE OF STUDY: 00/72
GROUP #: 1
FUEL: 11.4% ASH, 3.4% SULFUR

COAL PREPARATION: WASHED: <3"DIA(<4 MESH)
COAL SOURCE: PEABODY, S.ILL.
CONTROL DEVICE: ESP

ELEMENT	COAL (FFM)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AL	11290.00	72.2	25.0	2.8	100
AS	4.30	19.9	72.0	8.1	43
BA	85.00	78.0	21.5	0.5	97
CA	4103.00	79.7	19.9	0.4	96
CD	0.46	.	.	.	.
CL	380.00	.	.	.	.
CO	3.95	55.7	43.4	0.5	98
CP	22.00	59.2	36.1	1.7	128
CS	1.50	54.7	44.8	0.5	105
CU	66.00	62.5	36.4	1.2	60
FE	15950.00	70.1	28.9	0.5	106
K	2180.00	64.1	35.2	0.8	89
MG	1610.00	67.6	30.0	2.4	101
MN	1510.00	74.8	24.1	1.1	112
NA	677.00	56.1	42.8	1.1	89
PP	7.40	7.0	90.7	2.4	91
SP	1.00	.	.	.	.
SE	3.00	41.0	33.3	25.6	79
TI	550.00	62.3	36.7	1.0	91
U	2.40	63.9	35.2	1.0	103
V	37.00	58.8	39.8	1.4	124
ZN	97.00	3.6	93.9	2.5	65

PLANT NAME: TA ALLEN-UNIT #2
REFERENCE NUMBER: T-1
BOILER TYPE: CYCLONE, 200 MW
AUTHORS: W.S. LYON
DATE OF STUDY: 00/73
GROUP #: 2
FUEL: 10.4% ASH, 3.1% SULFUR

COAL PREPARATION: WASHED, CRUSHED, <3" (<4 MESH)
COAL SOURCE: PFABODY, SOUTH ILL.
CONTROL DEVICE: ESP

ELEMENT	COAL (PPM)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AL	10440.00	56.1	43.7	0.2	100
AS	5.00	15.3	82.7	2.0	130
BA	65.00	43.2	56.5	0.3	101
CA	4340.00	62.0	37.8	0.2	98
CD	0.47	12.8	84.2	3.0	99
CL	9.40	35.3	64.7	.	2
CO	2.50	38.2	61.4	0.5	109
CR	18.00	36.8	62.3	0.8	133
CS	1.10	37.3	62.1	0.6	100
CU	8.30	14.1	85.3	0.6	98
FE	10850.00	51.2	48.5	0.3	116
HC	0.12	.	.	.	.
K	1540.00	47.2	52.5	0.3	124
MG	1210.00	57.1	42.9	.	102
MN	33.80	53.1	46.9	.	94
MO	6.00	11.8	88.2	.	131
NA	696.00	35.7	63.9	0.3	115
NI	16.00	30.3	69.3	0.4	100
PP	4.50	7.5	89.4	3.1	89
SE	0.50	4.4	78.1	17.5	127
SE	2.20	0.0	81.8	18.2	78
SI	23100.00	57.1	42.9	.	99
TI	506.00	43.3	56.2	0.5	105
U	2.18	35.9	63.2	0.9	108
V	28.50	40.0	59.3	0.8	130
ZN	.	7.5	90.9	1.6	103

PLANT NAME: STATION I (PROPRIETARY)
REFERENCE NUMBER: T-2(VOL II)
BOILER TYPE: TANGENTIALLY-FIRED, BALANCED DRAFT CONTROL DEVICE: VENTURI-WET SCRUB
AUTHORS: RADIAN CORP FOR EPA REGION VIII
DATE OF STUDY: 10/75
GROUP #: 3

COAL PREPARATION: PULVERIZED
COAL SOURCE: WYOMING SUB-PITUMINOUS

ELEMENT	COAL (FFM)	EMISSION	HOPPER	EMISSIONS	CLOSURE
AS	0.04	9.5	85.8	4.7	114
AL	2300.00	18.0	81.7	0.3	101
AS	0.83	5.0	87.5	7.5	120
R	51.00	7.9	86.2	5.5	88
BA	130.00	15.4	83.7	0.8	133
BE	0.82	15.7	83.7	0.6	80
CA	1760.00	15.1	84.1	0.6	100
CD	0.18	8.9	84.1	7.0	170
CL	44.00	8.3	16.7	75.0	106
CO	2.10	15.5	81.9	2.6	99
CP	21.00	10.7	79.4	9.9	125
CU	34.00	12.4	87.0	0.7	90
F	140.00	0.0	98.0	2.0	100
FE	4000.00	20.2	79.2	0.6	126
HC	0.13	0.8	12.5	86.7	72
MS	2000.00	17.7	81.1	1.2	97
MN	170.00	13.6	86.0	0.4	113
MO	4.00	8.4	49.4	43.2	79
NI	9.00	18.3	77.6	4.1	108
PE	4.20	3.1	95.0	1.9	208
S	7200.00	0.0	37.8	62.2	88
SE	0.53	9.9	89.5	0.6	114
SF	2.20	4.6	93.7	1.7	114
TI	1100.00	29.6	79.1	0.3	81
U	1.30	50.2	47.8	2.0	83
V	51.00	16.3	81.2	2.5	120
ZN	24.00	4.4	93.1	2.5	138

PLANT NAME: STATION II (PROPRIETARY)
REFERENCE NUMBER: T-2 (VOL III)
ROILER TYPE: TANGENTIALLY-FIRED, 350 MW
AUTHORS: RADIAN CORP FOR EPA REGION VII
DATE OF STUDY: 10/75
GPCUP #: 4

COAL PREPARATION: CRUSHED, CONVEYER
COAL SOURCE: SUB-BITUMINOUS COAL, WYOMING
CONTROL DEVICE: HOT SIDE ESP

ELEMENT	CCAL (PPM)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AS	0.05	3.2	95.5	1.3	115
AL	7100.00	20.5	78.8	0.7	83
AS	2.50	0.8	99.1	0.1	100
B	31.00	12.1	83.2	4.7	116
BA	460.00	16.0	83.9	0.1	107
BE	0.29	16.9	81.1	2.0	138
CA	10000.00	18.5	80.7	0.8	123
CD	0.10	15.7	80.5	3.8	83
CL	9.40	16.0	3.8	80.2	344
CO	1.50	15.6	82.9	1.5	122
CP	9.30	13.9	73.7	12.4	96
CU	31.00	12.7	86.5	0.8	94
F	67.00	1.1	91.3	7.6	100
FE	2100.00	27.9	71.3	0.8	111
HS	0.14	2.1	0.0	97.9	14
MC	1500.00	17.2	82.0	0.8	126
MN	24.00	17.3	81.5	1.2	116
MO	0.64	12.8	77.8	9.4	94
NI	2.10	13.6	68.2	18.2	145
PE	2.30	10.3	82.2	7.5	65
S	4000.00	3.4	8.8	87.8	109
SB	0.16	2.7	93.4	3.9	113
SE	1.60	1.4	60.9	37.7	39
TI	565.00	21.1	78.3	0.6	119
U	0.95	18.0	80.5	1.5	44
V	20.00	15.3	82.3	2.4	100
ZN	4.10	29.4	68.0	2.6	147

PLANT NAME: STATION III (PROPRIETARY)
REFERENCE NUMBER: T-2 (VCL IV)
BOILER TYPE: CYCLONE 250 MW
AUTHORS: RADIAN CORP
DATE OF STUDY: 11/75
GROUP #: 5

COAL PREPARATION: CRUSHED, CONVEYOR
COAL SOURCE: NORTH DAKOTA LIGNITE
CONTROL DEVICE: MECHANICAL COLLECTOR

DUE TO UNUSUALLY HIGH PARTICULATE EMISSIONS, THESE DATA EXCLUDED FROM AVERAGES

ELEMENT	COAL (PPM)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AG	0.03	22.0	62.1	15.9	98
AL	7400.00	67.2	21.6	11.2	126
AS	P.00	16.8	62.7	20.4	100
B	150.00	21.0	24.8	54.2	116
BA	440.00	65.0	33.4	1.6	142
BE	0.60	58.4	35.1	6.5	107
CA	13800.00	60.3	23.1	16.6	113
CD	0.20	26.7	32.4	40.9	122
CL	55.00	12.2	7.6	80.2	131
CO	0.75	48.0	27.4	28.5	194
CR	13.00	44.2	15.4	40.3	116
CU	10.50	34.0	37.1	28.8	100
F	57.00	1.1	24.9	74.0	131
FE	7500.00	61.8	20.7	17.5	101
HG	0.07	0.8	3.1	96.1	213
MC	3700.00	62.1	23.1	14.8	115
MN	79.00	62.4	25.1	12.5	106
MO	2.00	15.3	20.9	62.9	406
NI	5.60	22.7	14.3	62.9	131
PE	0.86	7.8	27.7	64.5	95
S	14400.00	0.1	1.8	58.1	89
SE	0.40	15.9	6.2	77.9	90
SF	1.30	2.3	32.4	65.3	58
TI	350.00	69.1	23.0	7.9	104
U	1.50	29.9	42.5	27.7	50
V	15.00	61.0	14.1	24.9	112
ZN	7.80	13.7	34.1	52.6	127

PLANT NAME:FCUP CORNERS,UNIT #4
REFERENCE NUMBER:1-1
BOILER TYPE:PC,800 MB
AUTHORS:WANGEN, L.E. WIEKE,C.L.
DATE OF STUDY:07/76
GRUP #: 6
AC VAPOR DATA REPORTED

COAL PREPARATION:PULVERIZED
COAL SOURCE:NEW MEXICO SUBBITUMINOUS
CONTROL DEVICE:ESP

ELEMENT	COAL (PPM)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AL	31100.00	18.8	81.2	.	107
AS	2.20	2.0	98.0	.	105
R	100.00	11.1	88.9	.	47
BA	520.00	20.0	80.0	.	136
BF	1.27	16.9	83.1	.	66
CA	6370.00	22.1	77.9	.	104
CD	0.12	.	.	.	.
CO	1.36	20.0	80.0	.	89
CP	4.43	15.8	84.2	.	100
CU	13.40	14.6	85.4	.	89
F	160.50	8.2	91.8	.	18
FE	5070.00	20.7	79.3	.	125
HS	0.06	4.0	96.0	.	20
K	1370.00	18.5	81.4	.	127
MS	1170.00	18.8	81.2	.	120
MN	53.30	25.6	74.4	.	127
MO	1.46	20.0	80.0	.	113
NA	2600.00	19.0	81.0	.	121
NY	2.40	23.9	76.2	.	84
PE	13.20	8.8	91.2	.	110
S	2500.00	12.0	88.0	.	3
SE	0.32	4.1	95.9	.	82
SF	2.00	0.6	99.4	.	66
SI	60100.00	19.7	80.3	.	108
TY	1010.00	14.0	86.0	.	123
U	2.56	20.0	80.0	.	90
V	22.40	16.3	83.7	.	91
ZN	12.50	8.7	91.3	.	104

PLANT NAME:FOUR CORNERS,UNIT #5
REFERENCE NUMBER:T-3
BOILER TYPE:PC,800 MW
AUTHORS:VANGEN, L.F. WIENKE, C.L.
DATE OF STUDY:07/76
GROLF #: 7
NC VAPOR DATA REPORTED

COAL PREPARATION:PULVERIZED
COAL SOURCE:NEW MEXICO SUBBITUMINOUS
CONTROL DEVICE:ESP

ELEMENT	COAL(PFM)	ECTION	HOPPER	EMISSIONS	CLOSURE
AL	0.20	19.3	80.7	.	99
AS	3220.00	2.4	97.6	.	182
B	1.10	6.7	93.3	.	165
BA	90.60	11.1	88.9	.	200
BE	959.00	17.2	92.8	.	85
CA	1.51	21.5	78.1	.	102
CD	7150.00	.	.	.	.
CO	0.10	.	.	.	.
CR	2.00	7.7	92.3	.	285
CU	4.04	14.2	85.8	.	117
F	14.20	4.1	95.9	.	42
FE	44.00	20.2	79.8	.	99
HS	5004.00	13.3	86.7	.	32
K	0.08	20.0	80.0	.	106
MC	1576.00	18.0	82.0	.	98
MO	910.00	14.3	85.7	.	154
NO	40.40	42.9	57.1	.	236
NA	0.01	18.6	81.4	.	98
NI	2310.00	14.3	85.7	.	154
PD	4.04	9.5	90.5	.	192
S	6.35	.	.	.	.
SE	1554.00	4.8	95.2	.	57
SE	0.13	5.4	94.6	.	44
SI	2.00	20.5	79.5	.	103
TI	50270.00	.	.	.	.
V	2000.00	5.9	94.1	.	187
ZM	20.20	2.4	97.6	.	300
	6.00				

CRADLE CORPORATION

PLANT NAME: CHALK POINT, MARYLAND
 REFERENCE NUMBER: T-5
 BOILER TYPE: WATER WALL, 350 MW, 1600 C
 AUTHORS: GLADNEY, E.S. FFD THESIS
 DATE OF STUDY: 08/73
 GROUP #: 8

COAL PREPARATION: PULVERIZED, 50 MESH, 13% ASH
 COAL SOURCE: E PENN. & W VIRGINIA
 CONTROL DEVICE: ESP

ELEMENT	COAL (PPM)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AL	10300.00	8.7	88.1	3.2	72
AS	26.60	0.4	78.6	21.0	72
CA	1400.00	8.3	88.8	2.5	75
CO	5.81	9.8	86.2	4.0	81
CR	28.50	7.6	89.2	3.2	80
FE	13600.00	14.2	83.5	2.2	110
HG	0.26	0.1	0.4	59.4	42
MC	801.00	9.6	87.0	3.4	77
MN	38.50	8.5	88.5	3.0	110
NA	252.00	8.9	87.9	3.2	75
NI	25.10	7.7	87.4	4.9	68
PE	5.64	6.2	81.6	12.2	63
SP	1.02	5.6	80.9	13.4	66
SE	5.14	0.7	76.1	23.3	53
TI	1230.00	9.5	87.4	3.1	69
V	40.20	8.5	86.2	5.3	68
ZN	32.00	7.2	82.8	10.1	72

PLANT NAME: TA ALLEN-UNIT #2 (TENNESSEE)
REFERENCE NUMBER: T-5
BOILER TYPE: CYCLONE, 290 MW
AUTHORS: BOLTON, N.E. ET. AL.
DATE OF STUDY: 00/74
GROUP #: 9

COAL PREPARATION: CRUSHED
COAL SOURCE: PEABODY, ILL.
CONTROL DEVICE: ESP

ELEMENT	COAL (PPM)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AL	10600.00	67.5	31.9	0.6	82
AS	3.80	2.1	93.6	4.3	48
BA	79.00	.	.	.	.
CA	3000.00	81.3	18.4	0.3	78
CD	0.47	.	.	.	.
CO	3.30	61.6	35.2	3.2	81
CR	21.00	53.2	45.2	1.6	142
CS	1.90	46.1	53.5	0.4	100
FE	13000.00	68.9	28.2	2.5	97
HC	0.06	.	.	.	.
K	2200.00	54.8	43.8	1.4	67
MC	1700.00	61.1	36.6	2.3	34
MN	54.00	72.9	25.4	1.7	93
MO	20.00	.	.	.	.
NA	650.00	50.3	48.9	0.8	80
PE	7.40	.	.	.	97
SP	1.00	.	.	.	.
TI	710.00	64.0	35.0	1.0	57
U	1.67	64.0	35.4	0.6	111
V	21.00	58.8	40.7	0.5	91
ZN	85.00	.	.	.	.

PLANT NAME:PILOT PLANT
REFERENCE NUMBER:T-4
BOILER TYPE:COMBUSTION
AUTHORS:J.T. YEH, C.R. MCCANN, J.J. DEMETER, D. BIENSTOCK
DATE OF STUDY:00/74
GROUP #:10

COAL PREPARATION:PULVERIZED
COAL SOURCE:PITTSBURG SEAM IN PENNSYLVANIA
CONTROL DEVICE:BAG HOUSE

ONLY HG MEASURED IN VAPOR EMISSION

FLEMENT	COAL(PPM)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AS	8.30	1.3	98.7	.	91
BE	1.38	3.6	96.4	.	79
CD	0.14	6.1	93.9	.	59
HC	0.16	0.0	45.3	54.7	98
PD	7.90	2.5	97.5	.	64
SE	1.25	1.5	98.1	.	53

PLANT NAME: VALMONT-UNIT #5(COLORADO)
REFERENCE NUMBER: T-7
BOTTLER TYPE: CORNER FIRED, 180 MW
AUTHORS: KAAKINEN, J. L. JORDEN, R. M.
DATE OF STUDY: 00/75
GROUP #: 11

COAL PREPARATION: PULVERIZED
COAL SOURCE: WESTERN SUBBITUMINOUS
CONTROL DEVICE: ESP/SCRUBBER

ELEMENT	COAL (PPM)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AL	4000.00	17.6	78.4	4.0	110
CU	9.60	10.1	79.2	10.8	89
FE	3700.00	18.1	77.5	4.4	106
HS	0.07	.	.	.	.
MO	0.55	4.3	78.1	17.6	89
S	6000.00	.	.	.	.
SE	1.90	13.3	48.1	38.6	33
ZN	7.30	9.6	75.9	14.5	89

PLANT NAME: MICHIGAN FOLER PLANT (PROPRIETARY) COAL PREPARATION: PULVERIZED
 REFERENCE AUPEER: T-E COAL SOURCE: EASTERN KENTUCKY BITUMINOUS
 ROTLER TYPE: PC, 770 MW CONTROL DEVICE: COLSIDE ESP
 AUTHORS: RADIAN CORP (R. W. MANN)
 DATE OF STUDY: 07/81
 GROUP #: 12

ELEMENT	COAL (PPH)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AG	0.11	3.5	94.2	2.3	108
AL	1450.00	9.4	90.5	0.1	98
AS	5.32	4.2	95.5	0.3	98
B	29.80	0.9	88.0	11.1	108
BA	131.11	7.8	92.0	0.2	110
BE	2.68	7.3	92.7	0.0	97
CD	0.08	0.4	96.7	2.9	108
CL	1710.00	0.0	9.0	100	199
CR	17.20	7.9	88.5	3.6	101
CU	19.90	5.5	92.4	2.1	89
F	215.00	2.7	23.1	74.2	38
FE	3390.00	12.0	87.9	0.1	120
H3	0.17	2.8	40.6	56.6	29
MN	22.70	14.1	85.8	0.1	128
NI	13.50	6.3	87.5	6.2	106
PE	9.78	4.0	95.7	0.3	30
S	7510.00	0.0	2.1	97.9	107
SB	0.40	1.1	97.5	1.4	314
SE	2.60	0.2	51.4	48.4	114
ZN	17.00	4.0	95.2	0.8	78

PLANT NAME:BLACKDUG UNIT #1
REFERENCE NUMBER:T-5
BOILER TYPE:FC-60 MW
AUTHORS:RADIAN CORP
DATE OF STUDY:06/75
GROUP #:13

COAL PREPARATION:PULVERIZED
COAL SOURCE:INTERIOR PROVINCE
CONTROL DEVICE:ESP/SCRUBBER

FLEMFNT	CCAL (PPM)	ECYOM	HOPPER	EMISSIONS	CLOSURE
AS	0.36	13.9	58.6	27.5	144
B	76.60	10.2	62.4	27.4	98
BE	0.57	21.0	67.0	12.0	114
CD	0.31	11.6	45.2	43.2	97
CR	0.52	23.1	75.2	1.7	71
F	71.80	1.7	13.9	84.4	89
HG	0.05	2.6	10.3	27.1	67
MN	16.00	24.3	63.6	12.1	108
NI	4.10	21.7	65.5	12.8	132
PR	2.00	17.9	73.2	8.9	51
S	1200.00	.	.	.	.
SE	1.65	3.3	36.7	60.0	34
V	42.10	1.2	95.1	3.7	61

PLANT NAME: WESTERN POWER PLANT (PROPRIETARY) COAL PREPARATION: PULVERIZED
 REFERENCE NUMBER: T-10 COAL SOURCE: ARIZONA SUBBITUMINOUS
 BOILER TYPE: PC WALL-FIRED, 800 MW CONTROL DEVICE: ESP
 AUTHORS: RADIAN CORP
 DATE OF STUDY: 06/75
 GROUP #: 14

ELEMENT	COAL (PPM)	BOTTOM	HOPPER	EMISSIONS CLOSURE
AS	0.32.	2.5	59.4	38.1
BA	310.00	17.9	73.9	8.2
BE	0.52	17.0	79.3	3.7
CA	100.00	20.7	74.1	5.2
CD	0.29	15.0	48.4	36.6
CE	2.00	11.3	61.4	27.3
CU	46.00	13.5	67.6	18.9
F	60.00	0.8	25.5	73.7
HG	0.04	0.8	15.7	83.4
MC	1010.00	23.4	70.0	6.6
MO	0.45	1.0	7.2	91.8
NI	2.40	7.0	43.6	49.4
OP	1.20	3.5	37.0	59.5
SB	0.65	5.7	57.1	37.2
SE	2.00	0.3	63.5	36.2
TI	572.00	.	.	.
V	8.50	16.3	72.8	10.5
ZN	13.00	.	.	.

PLANT NAME: WESTERN POWER PLANT (PROPRIETARY)
REFERENCE NUMBER: T-11
BOILER TYPE: WALL-FIRED, 800 MW
AUTHORS: RADIAN CORP
DATE OF STUDY: 00/78
GROUP #: 15

COAL PREPARATION: PULVERIZED
COAL SOURCE: ARIZONA SUBBITUMINOUS
CONTROL DEVICE: ESP

ELEMENT	CCAL (PPM)	BOTTOM	HOPPER	EMISSIONS	CLOSURE
AL	11000.00	24.6	73.6	1.8	97
AS	2.60	25.6	71.4	3.0	131
B	36.00	29.2	67.0	3.8	119
BA	190.00	22.2	77.0	0.8	109
BE	0.45	21.7	76.7	1.6	79
CD	0.05	6.2	85.4	8.4	107
CL	260.00	3.2	10.6	86.2	17
CO	1.80	16.2	80.3	3.5	199
CR	6.80	16.3	80.8	2.9	93
F	30.00	1.2	41.9	56.9	74
FE	2400.00	22.6	75.5	1.5	121
HS	0.16	0.6	5.6	93.8	167
K	240.00	21.0	76.0	3.0	79
MG	950.00	21.2	76.1	2.7	104
MO	1.30	1.1	98.4	0.5	289
NI	2.20	17.3	77.2	5.5	77
PP	4.00	4.0	91.3	4.7	130
S	4000.00	0.3	4.4	95.3	.
SE	0.70	22.5	75.4	2.1	100
SE	0.60	0.9	59.7	39.4	91
TI	700.00	22.6	75.3	2.1	80
U	1.80	16.6	78.9	4.5	42
V	12.00	19.9	75.4	4.7	69
ZN	6.40	14.2	77.3	8.5	86

TABLE V-2

Elemental distributions and enrichments with
respect to aluminum grouped by elements for
pulverized coal boilers.

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: AG

GROUP	COAL (PPM)	ECCTOM ASH (%)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	0.04	5.5	85.6	1.964	4.7	23.474	114
4	0.05	3.2	95.5	1.168	1.3	5.199	115
7	0.20	.	.	.	.	.	.
12	0.11	3.5	94.2	1.202	2.3	0.575	108
AVERAGE	0.10	5.4	91.8	1.445	2.8	6.750	112
STD DEV	0.07	3.5	5.2	0.450	1.7	12.100	4

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: AL

GROUP	CCAL (PPM)	ECTON ASH (%)	ECTON ASH (/AL)	TCP ASH (%)	TCP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	23060.00	18.0	1.000	81.7	1.000	0.3	1.000	101
4	7100.00	20.5	1.000	78.8	1.000	0.7	1.000	83
6	31100.00	18.8	1.000	81.2	1.000	0.0	.	107
7	32200.00	19.3	1.000	80.7	1.000	0.0	.	99
8	19300.00	8.7	1.000	88.1	1.000	3.2	1.000	72
11	4900.00	17.6	1.000	78.4	1.000	4.0	1.000	110
12	14500.00	9.4	1.000	90.5	1.000	0.1	1.000	98
15	11000.00	24.6	1.000	73.6	1.000	1.8	1.000	97
AVERAGE	17887.50	17.1	1.000	81.6	1.000	1.2	1.000	96
STD DEV	10761.39	5.4	0.000	5.4	0.000	1.6	0.000	12

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: AS

GROUP	CCAL (PPM)	ECTION ASH (%)	TOP ASH (%)	VAPOR (/AL)	CLOSURE (%)
2	0.83	5.0	87.5	7.5	120
4	2.50	0.8	99.1	0.1	100
6	2.20	2.0	98.0	0.0	105
7	1.10	2.4	97.6	0.0	182
8	26.67	0.4	78.6	21.0	72
10	8.30	1.3	98.7	0.0	81
12	5.32	4.2	95.5	0.3	98
13	0.76	13.0	58.6	27.5	144
14	0.72	2.5	59.4	38.1	108
15	2.60	25.6	71.4	3.0	131
				1.667	
AVERAGE	5.01	5.8	84.4	9.7	114
STD DEV	7.98	8.0	16.4	14.0	32
				1.054	
				0.136	
				12.279	

CORPORATION

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

FLEMENT:B

GROUP	CCAL (FFM)	ECTOM ASH (%)	ECTOM ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLCSURE (%)
3	51.00	7.0	0.439	86.2	1.055	5.9	23.583	48
4	31.00	12.1	0.590	83.2	1.056	4.7	6.714	116
5	105.00	11.1	0.592	88.5	1.054	0.0	.	47
7	80.60	6.7	0.347	93.3	1.156	0.0	.	165
12	25.80	0.0	0.056	88.0	0.972	11.1	138.72	100
13	76.60	10.2	.	62.4	.	27.4	.	98
15	36.00	25.2	1.187	67.0	0.010	3.8	2.111	119

AVFRAGE
STD DEV

58.57
25.21
7.6
9.5
42.783
64.622
106
76

81.3
11.8
1.041
0.088

11.2
8.8
0.542
0.366

ENRICHMENT IN STREAKS WITH RESPECT TO ALUMINUM

ELEMENT: BA

GROUP	CCAL (FFM)	ECTION (%)	ASH (/AL)	TOP ASH (%)	ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	130.00	15.4	0.856	83.7	1.024	0.8	3.364	133
4	460.00	16.0	0.781	83.9	1.065	0.1	0.129	107
5	520.00	20.0	1.065	80.0	0.985	0.0	.	136
7	595.00	11.1	0.875	88.5	1.102	0.0	.	200
12	131.00	7.8	0.830	92.0	1.016	0.2	2.375	110
14	310.00	17.5	.	73.5	.	8.2	.	98
15	150.00	22.2	0.502	77.0	1.046	0.8	0.444	109
AVERAGE	351.43	15.8	0.835	82.8	1.040	1.4	1.578	128
STD DEV	309.23	5.0	0.160	6.4	0.041	3.0	1.550	35

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: BE

GROUP	CCAL (PPM)	ECTION (%)	ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	0.82	15.7	0.670	83.7	1.024	0.6	2.595	87
4	0.26	16.6	0.825	81.1	1.025	2.0	2.860	138
6	1.27	16.6	0.899	83.1	1.023	0.0	.	66
7	1.51	17.2	0.891	82.8	1.026	0.0	.	85
10	1.38	3.6	.	96.4	.	0.0	.	79
12	2.68	7.3	0.776	92.7	1.024	0.0	0.087	97
13	0.57	21.0	.	67.0	.	12.0	.	114
14	0.52	17.0	.	79.3	.	3.7	.	86
15	0.46	21.7	0.882	76.7	1.042	1.6	0.889	79
AVERAGE	1.06	15.3	0.857	82.8	1.028	2.2	1.608	92
STD DEV	0.75	6.0	0.047	8.6	0.007	3.5	1.338	22

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: CA

GROUP	CCAL (PPM)	ECTICH (%)	ASH (/AL)	TOP (%)	ASH (/AL)	(%)	VAPOR (/AL)	CLOSURE (%)
3	17600.00	15.1	0.839	84.1	1.028	0.8	3.400	100
4	10900.00	18.5	0.902	80.7	1.024	0.8	1.143	123
6	6370.00	22.1	1.176	77.5	0.959	0.0	.	104
7	7150.00	21.8	1.135	78.1	0.968	0.0	.	102
8	1450.00	8.2	0.955	88.8	1.008	2.9	0.904	75
14	8100.00	20.7	.	74.1	.	5.2	.	87
AVERAGE	8601.67	17.8	1.001	80.6	0.997	1.6	1.816	99
STD DEV	5769.68	5.3	0.147	5.2	0.032	2.0	1.377	16

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: CD

GROUP	CCAL (PPM)	ECTTCM (%)	ASH (/AL)	TOP ASP (%)	TOP ASP (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	0.118	8.9	0.494	84.1	1.329	7.0	27.975	170
4	0.110	15.7	0.766	80.5	1.322	3.8	5.429	83
6	0.12	.	.	.	.	.	.	.
7	0.110	.	.	.	.	.	.	.
10	0.14	6.1	.	93.6	.	0.0	.	59
12	0.09	0.4	0.043	96.7	1.068	2.5	36.243	108
13	0.31	11.6	.	45.2	.	43.2	.	97
14	0.29	15.0	.	48.4	.	36.6	.	92
15	0.05	6.2	0.252	85.4	1.160	8.4	4.667	107
AVERAGE	0.15	9.1	0.389	76.3	1.070	14.6	18.578	102
STD DEV	0.05	5.4	0.312	20.9	0.064	17.6	15.987	34

FARICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT:CL

GROUP	CCAL (FFM)	ECTOM ASH (%)	ECTOM ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	44.00	8.2	0.461	16.7	0.204	75.0	299.91	106
4	5.40	16.0	0.780	3.8	0.048	80.2	114.57	344
12	1710.00	0.0	0.000	0.0	0.000	100	1249.8	199
15	260.00	2.2	0.130	10.6	0.144	86.2	47.889	17
AVERAGE	505.85	6.6	0.343	7.8	0.099	85.3	428.03	167
STD DEV	210.39	7.0	0.350	7.4	0.092	10.8	558.09	140

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

GROUP	CCAL (FFM)	ECTION ASH (%)	(/AL)	TOP ASH (%)	(/AL)	VAPOR (%)	CLOSURE (%)
3	2.10	15.5	0.862	81.9	1.002	2.6	90
4	1.50	15.6	0.761	82.9	1.052	1.5	122
5	1.76	20.0	1.065	80.0	0.985	0.0	80
7	2.00	.	.	.	.	.	.
8	5.81	5.8	1.126	86.2	0.978	4.0	81
15	1.80	16.2	0.659	80.2	1.051	3.5	100
AVERAGE	2.42	15.4	0.895	82.3	1.022	2.3	98
STD DEV	1.68	3.7	0.198	2.5	0.048	1.6	17

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: CR

GRUPE	CCAL (PPM)	ECTCM (%)	ASH (/AL)	TOP (%)	ASF (/AL)	VAPOR (%)	CLOSURE (%)
3	21.00	10.7	0.594	79.4	0.971	9.9	125
4	5.30	17.6	0.678	73.7	0.935	12.4	96
6	4.43	15.8	0.841	84.2	1.037	0.0	100
7	4.04	7.7	0.359	92.3	1.144	0.0	285
8	28.90	7.6	0.872	89.2	1.012	3.2	80
12	17.20	7.9	0.840	88.5	0.978	3.6	101
13	0.62	23.1	.	75.2	.	1.7	71
14	2.00	11.3	.	61.4	.	27.3	138
15	6.80	16.3	0.663	80.8	1.098	2.9	93
AVERAGE	10.51	12.7	0.658	80.5	1.025	6.8	121
STD DEV	5.65	5.2	0.170	5.6	0.074	8.8	65

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: CU

GROUP	CCAL (FFM)	ECTOM ASH (%)	ECTOM ASH (/AL)	TCP ASF (%)	TCP ASF (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	34.00	12.4	0.688	87.0	1.064	0.7	2.637	90
4	31.00	12.7	0.620	86.5	1.058	0.8	1.143	94
6	13.40	14.6	0.777	85.4	1.051	0.0	.	89
7	14.20	14.2	0.736	85.8	1.063	0.0	.	117
11	8.60	10.1	0.573	79.2	1.010	10.8	2.691	89
12	19.50	8.5	0.585	92.4	1.321	2.1	26.245	89
14	46.00	13.5	.	67.6	.	18.9	.	15
AVERAGE	24.01	11.0	0.663	83.4	1.051	4.7	8.179	83
STD DEV	13.33	3.2	0.084	8.0	0.032	7.3	12.065	32

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: F

CIRCLE	COAL (PPM)	BOTTOM ASH (%)	TOP ASH (%)	TOP ASH (%/AL)	VAPOR (%)	VAPOR (%/AL)	CLOSURE (%)
3	140.00	0.0	98.0	1.199	2.0	7.998	100
4	67.00	1.1	91.3	1.159	7.5	10.857	100
6	160.50	8.2	91.8	1.120	0.0	.	18
7	44.00	4.1	95.9	1.188	0.0	.	42
12	215.00	2.7	23.1	0.287	74.2	927.31	38
13	71.00	1.7	13.0	.	84.4	.	89
14	60.00	0.8	25.5	.	73.7	.	124
15	30.00	1.2	41.9	0.569	56.9	31.611	74
AVERAGE	95.66	2.5	60.2	0.917	37.4	244.45	73
STD DEV	64.17	2.6	37.3	0.404	38.2	455.37	37

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT:FE

GROUP	CCAL (PPM)	ECTION ASH (%)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	4000.00	20.2	79.2	0.969	0.6	2.493	126
4	2100.00	27.5	71.3	0.905	0.8	1.143	111
6	5070.00	20.7	79.3	0.977	0.0	.	125
7	5954.00	20.2	79.8	0.985	0.0	.	99
8	13600.00	14.2	83.5	0.946	2.3	0.710	110
11	3700.00	18.1	77.5	0.989	4.4	1.100	106
12	3350.00	12.0	87.9	0.971	0.1	1.125	120
15	2400.00	22.6	75.6	1.026	1.9	1.056	121
AVERAGE	5031.75	19.5	79.3	0.972	1.3	1.273	115
STD DEV	3651.63	4.5	5.0	0.035	1.5	0.618	10

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: HS

GROUP	CCAL (PPM)	ECTON ASH (%)	TOP ASH (%)	VAPOR (%)	CLOSURE (%)
3	0.13	0.043	12.5	86.7	72
4	0.14	0.102	0.0	57.9	14
6	0.06	0.213	96.0	0.0	20
7	0.08	0.689	86.7	0.0	32
8	0.36	0.014	0.4	59.4	42
10	0.15	.	45.3	54.7	98
11	0.07	.	.	.	11
12	0.17	0.298	40.6	56.6	28
13	0.05	.	10.3	87.1	67
14	0.04	.	15.7	83.4	128
15	0.16	0.026	5.6	53.8	167
AVERAGE	0.13	0.198	31.3	66.0	62
STD DEV	0.09	0.241	35.2	38.0	51
			0.420	255.51	
			0.508	281.74	

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT:K

GROUP	CCAL (PPM)	ECTTCM (%)	ASH (/AL)	TCP (%)	ASH (/AL)	VAPOR (%)	CLOSURE (%)
6	1370.00	18.6	0.591	81.4	1.002	0.0	127
7	1576.00	20.0	1.036	80.0	0.951	0.0	106
15	240.00	21.0	0.854	76.0	1.033	3.0	79
						1.667	
AVERAGE	1062.00	19.9	0.960	79.1	1.009	1.0	104
STD DEV	719.29	1.2	0.095	2.8	0.021	1.7	24
						1.667	
						.	

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENTS

GROUP	COAL (FFM)	FCYCLM ASH (%)	FCYCLM ASH (/AL)	TCP ASH (%)	TCP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	2000.00	17.7	0.983	81.1	0.982	1.2	4.797	87
4	1500.00	17.2	0.839	82.0	1.041	0.8	1.143	126
6	1100.00	18.8	1.003	81.2	0.999	0.0	.	120
7	510.00	18.0	0.933	82.0	1.016	0.0	.	98
8	891.00	9.6	1.105	87.0	0.987	3.4	1.062	77
14	1010.00	27.4	.	70.0	.	6.6	.	102
15	950.00	21.2	0.862	76.1	1.024	2.7	1.500	104

AVERAGE	1323.00	18.0	0.954	79.9	1.012	2.1	2.126	103
STD DEV	725.59	4.3	0.098	5.4	0.022	2.4	1.791	16

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: MN

GRUP	CCAL (FPM)	BOTTOM ASH (%)	(/AL)	TOP ASH (%)	(/AL)	VAPOR (%)	(/AL)	CLOSURE (%)
3	170.00	13.6	0.756	86.0	1.052	0.4	1.521	113
4	24.00	17.3	0.844	81.5	1.034	1.2	1.714	116
6	53.30	25.6	1.363	74.4	0.916	0.0	.	127
7	40.40	14.3	0.741	85.7	1.062	0.0	.	154
8	38.50	8.5	0.920	88.5	1.004	3.0	0.948	110
12	22.70	14.1	1.499	85.8	0.947	0.1	1.749	128
13	186.00	24.3	.	63.6	.	12.1	.	108
AVERAGE	76.41	16.8	1.031	80.8	1.003	2.4	1.483	122
STD DEV	70.32	6.1	0.325	8.5	0.055	4.4	0.370	16

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: MO

GROUP	COAL (PPM)	ECTION ASH (%)	ECTION ASH (%AL)	TOP ASH (%)	TOP ASH (%AL)	VAPOR (%)	VAPOR (%AL)	CLOSURE (%)
3	4.00	8.4	0.467	48.4	0.552	43.2	172.77	79
4	0.64	12.8	0.624	77.8	0.987	9.4	13.429	94
6	1.46	20.0	1.065	80.0	0.985	0.0	.	113
7	0.81	42.9	2.223	57.1	0.708	0.0	.	236
11	0.89	4.3	0.244	78.1	0.996	17.6	4.400	89
14	0.45	1.0	.	7.2	.	91.8	.	89
15	1.30	1.1	0.045	98.4	1.337	0.5	0.278	280
AVERAGE	1.39	12.8	0.778	63.9	0.934	23.2	47.718	141
STD DEV	1.21	14.0	0.789	29.8	0.261	34.0	83.546	85

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: NA

GROUP	CCAL (PPM)	ECTICM ASH (%)	ECTICM ASH (/AL)	TCP ASH (%)	TCP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLCSURE (%)
6	2650.00	15.0	1.012	81.0	0.997	0.0	.	121
7	2310.00	18.6	0.964	81.4	1.009	0.0	.	98
8	2920.00	8.9	1.023	87.9	0.998	3.2	0.998	75
AVERAGE	1764.00	15.5	1.000	83.4	1.001	1.1	0.998	98
STD DEV	1288.87	5.7	0.032	3.5	0.006	1.8	.	23

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: NI

GROUP	COAL (FFM)	ECTON ASH (%)	ECTON ASH (/AL)	TCP ASH (%)	TCP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	9.00	18.2	1.016	77.6	0.949	4.1	16.392	108
4	2.10	13.6	0.663	68.2	0.865	18.2	26.000	145
6	2.40	23.8	1.267	76.2	0.938	0.0	.	84
7	4.04	14.3	0.741	85.7	1.062	0.0	.	154
8	25.10	7.7	0.887	87.4	0.951	4.9	1.556	68
12	13.50	6.3	0.670	87.5	0.967	6.2	77.485	106
13	4.10	21.7	.	65.5	.	12.8	.	172
14	2.40	7.0	.	43.6	.	49.4	.	141
15	2.20	17.3	0.703	77.2	1.049	5.5	3.056	77
AVERAGE	7.20	14.4	0.850	74.3	0.975	11.2	24.898	113
STD DEV	7.75	6.4	0.225	13.9	0.068	15.4	31.068	32

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: PB

GROUP	CCAL (PPM)	ECTICH (%)	ASH (/AL)	TOP (%)	ASH (/AL)	(%)	VAPOR (/AL)	CLOSURE (%)
3	4.20	3.1	0.172	95.0	1.162	1.9	7.606	208
4	2.30	10.3	0.502	82.2	1.043	7.5	10.714	65
6	13.20	8.8	0.469	91.2	1.123	0.0	.	110
7	6.35	5.5	0.492	90.5	1.121	0.0	.	192
8	5.64	6.2	0.717	81.6	0.925	12.2	3.850	63
10	7.80	2.5	.	97.5	.	0.0	.	64
12	9.78	4.0	0.426	95.7	1.057	0.3	3.500	30
13	2.00	17.9	.	73.2	.	8.9	.	51
14	1.20	3.5	.	37.0	.	59.5	.	82
15	4.00	4.0	0.163	91.3	1.240	4.7	2.611	130
AVERAGE	6.06	7.0	0.420	83.5	1.056	9.5	5.556	100
STD DEV	3.95	4.8	0.196	18.0	0.100	18.1	3.412	60

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT:S

GROUP	CCAL (FPM)	ECOTOM ASH (%)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	7200.00	1.0	37.8	0.462	62.2	248.78	88
4	4500.00	3.4	8.0	0.112	67.8	125.43	109
6	2500.00	12.0	88.7	1.083	0.0	.	3
7	1554.00	.	.	.	.	.	.
11	4000.00	.	.	.	.	.	.
12	7910.00	0.0	2.1	0.023	57.9	1223.5	107
13	13200.00	.	.	.	.	.	N
15	4000.00	0.3	4.4	0.060	55.3	52.944	.
AVERAGE	5908.00	3.1	28.2	0.348	68.6	412.66	77
STD DEV	3666.20	5.2	36.4	0.447	40.9	546.57	50

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: SE

GROUP	CCAL (FPM)	BOTTOM ASH (%)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	0.53	5.5	89.5	1.092	0.6	2.441	114
4	0.16	2.7	93.4	1.185	3.9	5.571	113
6	0.32	4.1	95.5	1.181	0.0	.	82
7	0.13	4.8	95.2	1.180	0.0	.	57
8	1.52	5.6	80.5	0.918	13.4	4.240	66
12	0.40	1.1	97.5	1.077	1.4	17.497	314
14	0.69	5.7	57.1	.	37.2	.	75
15	0.70	22.5	75.4	1.024	2.1	1.167	100
AVERAGE	0.45	7.1	85.6	1.054	7.3	6.183	115
STD DEV	0.30	6.7	13.5	0.055	12.9	6.544	83

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: SE

GROUP	CCAL (FFW)	ECTION (%)	ASH (/AL)	TOP (%)	ASH (/AL)	(%)	VAPOR (/AL)	CLOSURE (%)
3	2.20	4.6	0.256	93.7	1.146	1.7	6.799	114
4	1.60	1.4	0.068	60.9	0.773	37.7	53.857	39
6	2.00	0.6	0.035	99.4	1.223	0.0	.	66
7	2.80	5.4	0.280	54.6	1.172	0.0	.	44
8	5.14	0.7	0.077	76.1	0.863	23.3	7.337	53
10	1.25	1.5	.	98.1	.	0.0	.	53
11	1.80	13.3	0.756	48.1	0.614	38.6	0.650	33
12	2.60	0.0	0.021	51.4	0.568	48.4	604.88	114
13	1.65	2.3	.	36.7	.	60.0	.	34
14	2.00	0.3	.	63.5	.	36.2	.	68
15	0.60	0.9	0.037	59.7	0.911	39.4	21.889	91
AVERAGE	2.16	3.0	0.191	71.1	0.856	25.9	117.4	64
STD DEV	1.16	3.9	0.250	22.4	0.255	22.1	239.48	30

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: SI

GROUP	COAL (PPM)	EXTRACT (%)	ASH (%/AL)	TOP ASH (%)	TOP ASH (%/AL)	VAPOR (%)	VAPOR (%/AL)	CLOSURE (%)
6	60100.00	15.7	1.049	80.3	0.985	0.0	.	108
7	50270.00	20.5	1.061	75.5	0.985	0.0	.	103
AVERAGE	59685.00	20.1	1.055	79.0	0.987	0.0	.	105
STD DEV	586.50	0.6	0.009	0.6	0.002	0.0	.	4

CORPORATION

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: TI

GROUP	CCAL (PPM)	ECTCM ASH (%)	(/AL)	TCP ASH (%)	(/AL)	(%)	VAPOR (/AL)	CLOSURE (%)
3	1100.00	20.6	1.145	79.1	0.967	0.3	1.200	91
4	565.00	21.1	1.029	78.3	0.954	0.6	0.857	119
6	1010.00	14.0	0.745	86.0	1.059	0.0	.	123
7	2000.00	.	.	.	.	.	.	.
8	1230.00	6.5	1.088	87.4	0.952	3.1	0.984	69
14	572.00	.	.	.	.	.	.	81
15	700.00	22.6	0.519	75.3	1.023	2.1	1.167	80

AVERAGE	1025.25	17.6	0.585	81.2	1.007	1.2	1.052	92
STD DEV	503.48	5.6	0.158	5.2	0.035	1.3	0.161	23

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: U

GROUP	CCAL (PPM)	ECTICM (%)	ASH (/AL)	TCP (%)	ASH (/AL)	VAPOR (%)	CLOSURE (%)
3	1.30	50.2	2.787	47.8	0.585	2.0	83
4	0.88	18.0	0.878	80.5	1.022	1.5	44
6	2.86	20.0	1.065	80.0	0.585	0.0	90
15	1.80	16.6	0.675	78.9	1.072	4.5	42

AVERAGE	1.64	26.2	1.351	71.8	0.916	2.0	65
STD DEV	0.72	16.0	0.570	16.0	0.223	1.9	25

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: V

GROUP	CCAL (PPM)	ECTOM (%)	ASH (/AL)	TOP (%)	ASH (/AL)	VAPOR (%)	CLOSURE (%)
3	51.00	16.2	0.906	81.2	0.993	2.5	120
4	20.00	15.2	0.746	82.3	1.044	2.4	100
6	23.40	16.2	0.868	83.7	1.021	0.0	91
7	20.20	5.5	0.206	94.1	1.166	0.0	187
8	40.20	8.5	0.982	86.2	0.978	5.3	68
13	42.10	1.2	.	95.1	.	3.7	61
14	9.80	16.2	.	72.8	.	10.9	103
15	12.00	15.9	0.809	75.4	1.024	4.7	69
AVRAGE	27.10	12.5	0.770	83.8	1.039	3.7	100
STD DEV	15.34	6.5	0.241	7.9	0.067	3.5	41
						4.428	
						3.787	

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM

ELEMENT: ZN

GROUP	CCAL (FFM)	ECTOM ASH (%)	ECTOM ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
3	24.00	4.4	0.245	93.1	1.139	2.5	10.007	138
4	4.10	29.4	1.434	68.0	0.863	2.6	3.714	147
6	12.50	2.7	0.463	91.3	1.124	0.0	.	104
7	6.06	2.4	0.124	97.6	1.209	0.0	.	300
8	32.00	7.2	0.824	82.8	0.939	10.1	3.150	72
11	7.30	9.6	0.545	75.6	0.968	14.5	3.625	89
12	17.00	4.0	0.425	95.2	1.052	0.8	9.998	78
14	13.00	.	.	.	.	.	.	125
15	6.40	14.2	0.577	77.3	1.050	8.5	4.722	86
AVERAGE	13.60	10.0	0.580	85.1	1.043	4.9	5.874	127
STD DEV	9.34	6.7	0.405	10.7	0.115	5.4	3.237	70

TABLE V-3

Elemental distributions and enrichments with respect to aluminum grouped by element for cyclonic-fired boilers. NOTE: Study #5 was on a facility with a mechanical cyclone for particulate control and a high emissions rate; as such emissions data from Study #5 are generally uncharacteristic, and for elements reported only by Study #5 (As, B, Be, F, S), the data have not been included (but remain in Table V-1).

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: AL

GROUP	COAL (PPM)	ECATCH (%)	ECATCH ASH (%/AL)	TCP (%)	TCP ASH (%/AL)	VAPOR (%)	CLOSURE (%)
1	11250.00	72.2	1.000	25.0	1.000	2.8	100
2	10440.00	56.1	1.000	43.7	1.000	0.2	100
3	7400.00	67.2	1.000	21.6	1.000	11.2	126
5	10600.00	67.5	1.000	31.5	1.000	0.6	82
AVERAGE	9972.50	65.7	1.000	30.5	1.000	3.7	102
STD DEV	1728.15	6.8	0.000	9.8	0.000	5.1	18

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
 BOILER TYPE: CYCLONE

ELEMENT: AS

GROUP	CCAL (PPM)	ECTOM ASH (%)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	4.30	19.9	72.0	2.884	8.1	2.857	43
2	5.00	15.1	82.7	1.852	2.0	10.217	130
5	8.00	16.8	62.7	2.903	20.4	1.825	100
9	3.80	2.1	93.6	2.935	4.3	6.721	48
AVERAGE	5.27	13.5	77.8	2.654	8.7	5.405	80
STD DEV	1.88	7.9	13.3	0.508	8.2	3.838	42

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
EOILER TYPE: CYCLONE

ELEMENT: BA

GRUP	COAL (FPM)	ECTICH ASH (%)	ECTICH ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	85.00	78.0	1.080	21.5	0.861	0.5	0.182	97
2	65.00	43.2	0.770	56.5	1.253	0.3	1.482	101
5	40.00	65.0	0.568	33.4	1.545	1.6	0.143	142
5	79.00	.	.	.	.	.	.	.
AVERAGE	167.25	62.1	0.939	37.1	1.233	0.8	0.602	113
STD DEV	182.33	17.6	0.157	17.8	0.346	0.7	0.762	25

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CORPORATION

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: BR

GROUP	CCAL (PPH)	ECTTCM (%)	ASH (/AL)	TOP ASH (%)	VAPOR (/AL)	CLOSURE (%)
1	2.30	14.2	0.198	78.6	2.1	2.534
2	2.70	35.8	0.709	60.2	0.0	0.000
AVERAGE	2.00	27.0	0.454	69.4	3.6	1.267
STD DEV	0.69	18.0	0.362	13.0	5.1	1.792

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
 BOILER TYPE: CYCLONE

ELEMENT: CA

GROUP	CCAL (FFM)	ECTCM (%)	ASH (/AL)	TOP (%)	ASH (/AL)	VAPOR (%)	CLOSURE (%)
1	4102.00	75.7	1.104	19.5	0.757	0.4	96
2	4340.00	62.0	1.106	37.8	0.864	0.2	98
5	13800.00	60.3	0.897	23.1	1.069	16.6	113
6	3200.00	81.3	1.205	18.4	0.577	0.3	78
AVERAGE	6532.25	70.8	1.078	24.8	0.827	4.4	96
STD DEV	4845.55	11.2	0.130	8.5	0.203	8.2	14

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

FLEMENT: CD

GROUP	CCAL (PPM)	ECTIOM ASH (%)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	0.46	.	84.2	1.927	3.0	14.808	.
2	0.47	12.8	32.4	1.459	40.9	3.655	99
F	0.20	26.7	.	.	.	.	122
9	0.47	.	.	.	.	.	109
AVERAGE	0.40	15.8	58.3	1.713	21.9	9.231	110
STD DEV	0.12	5.8	36.7	0.303	26.9	7.886	12

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: CL

GROUP	COAL (FFM)	ECTOM ASH (%)	ECTOM ASH (/AL)	TCP ASH (%)	TCP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	380.00	35.3	0.629	64.7	1.480	0.0	0.000	2
2	9.40	12.2	0.182	7.6	0.353	80.2	7.157	131
5	55.00							
AVERAGE	148.13	23.8	0.406	36.2	0.916	40.1	3.579	67
STD DEV	202.05	16.3	0.316	40.4	0.757	56.7	5.061	91

BRANDAL
CORPORATION

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
ECILER TYPE: CYCLONE

ELEMENT: CO

GROUP	CCAL (PPM)	ECITOM ASH (%)	ECITOM ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	3.95	55.7	0.772	43.4	1.737	0.9	0.323	98
2	2.80	38.2	0.680	61.4	1.404	0.5	2.281	109
5	0.75	48.0	0.715	23.4	1.084	28.5	2.547	194
6	3.30	61.6	0.913	35.2	1.104	3.2	5.002	81
AVERAGE	2.72	50.8	0.770	40.8	1.332	8.3	2.538	121
STD DEV	1.39	10.1	0.102	16.0	0.307	13.6	1.919	50

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: CR

GROUP	COAL (PPM)	ECTTCM ASH (%)	ECTTCM ASH (/AL)	TCP ASH (%)	TCP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	22.00	55.2	0.820	39.1	1.565	1.7	0.600	128
2	18.00	36.8	0.657	62.3	1.426	0.8	4.061	133
5	13.00	44.2	0.658	15.4	0.714	40.3	3.602	116
9	21.00	53.2	0.788	45.2	1.417	1.6	2.501	142
AVERAGE	18.50	48.4	0.731	40.5	1.281	11.1	2.691	130
STD DEV	4.04	9.8	0.086	19.4	0.384	19.5	1.540	11

**ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
FOILER TYPE: CYCLONE**

ELEMENT: CS

GROUP	CCAL (PPM)	ECTOM (%)	ASH (/AL)	TOP (%)	ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	1.50	54.7	0.758	44.8	1.794	0.5	0.168	105
2	1.10	37.3	0.665	62.1	1.421	0.6	2.988	100
9	1.50	46.1	0.683	53.5	1.677	0.4	0.656	100
AVERAGE	1.37	46.0	0.702	53.5	1.631	0.5	1.271	102
STD DEV	0.23	8.7	0.049	8.7	0.191	0.1	1.507	3

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

FLEMENT: CU

GROUP	CCAL (PPM)	ECTCM ASH (%)	ECTCM ASH (/AL)	TCP ASH (%)	TCP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	66.00	62.5	0.865	36.4	1.456	1.2	0.411	60
2	8.30	14.1	0.251	85.3	1.952	0.6	3.039	98
5	10.50	34.0	0.506	37.1	1.719	28.8	2.575	100
AVERAGE	28.27	36.5	0.541	52.6	1.705	10.2	2.008	86
STD DEV	32.70	24.2	0.309	28.1	0.248	16.1	1.403	23

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FARICPMENT IN STREAMS WITH RESPECT TO ALUMINUM
EOILER TYPE:CYCLONE

ELEMENT:FF

GROUP	CCAL (FPM)	ECTTOM ASH (%)	ECTTOM ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	15850.00	70.1	0.971	28.5	1.159	0.9	0.331	106
2	10850.00	51.2	0.912	48.5	1.109	0.3	1.732	116
3	7500.00	61.8	0.520	20.7	0.958	17.5	1.562	101
9	13000.00	68.5	1.021	28.2	0.884	2.9	4.533	97
AVERAGE	11810.00	63.0	0.956	31.6	1.028	5.4	2.040	105
STD DEV	3538.37	8.7	0.051	11.5	0.128	8.1	1.776	8

BRADY
CORPORATION

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: HG

GROUP	CCAL (FPM)	ECTTCM (%)	ASH (/AL)	TCP (%)	ASH (/AL)	VAPOR (%)	CLOSURE (%)
2	0.12	.	0.012	3.1	0.145	96.1	.
5	0.07	0.8	.	.	.	8.578	213
5	0.06	.	.	.	.	.	15
AVERAGE	0.09	0.8	0.012	3.1	0.145	96.1	114
STD DEV	0.03	.	.	.	.	.	140

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
EOLIFP TYPE: CYCLONE

ELEMENT: K

GROUP	CCAL (FPM)	ECOTOM ASH (%)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	2180.00	64.1	35.2	1.408	0.8	0.277	89
2	1540.00	47.2	52.5	1.202	0.3	1.607	124
5	2200.00	54.8	43.8	1.374	1.4	2.188	67
AVERAGE	1973.33	55.2	43.8	1.328	0.8	1.358	93
STD DEV	375.41	8.5	8.7	0.110	0.5	0.980	29

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
CYCLONE TYPE: CYCLONE

ELEMENT: MG

GROUP	COAL (PPM)	ECTOM ASH (%)	ECTOM ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	1610.00	67.6	0.537	30.0	1.159	2.4	0.857	101
2	1210.00	57.1	1.019	42.5	0.980	0.0	0.000	102
5	3700.00	62.1	0.924	23.1	1.069	14.8	1.321	115
6	1700.00	61.1	0.906	36.6	1.148	2.3	3.595	34
AVERAGE	2055.00	62.0	0.946	33.1	1.055	4.9	1.443	88
STD DEV	1117.15	4.3	0.050	8.5	0.055	6.7	1.535	37

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: MN

GROUP	CCAL (PPM)	BOTTOM ASH (%)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	1510.00	74.8	24.1	0.965	1.1	0.376	112
2	33.00	53.1	46.5	1.074	0.0	0.000	.
5	70.00	62.4	25.1	1.164	12.5	1.114	106
9	54.00	72.9	25.4	0.757	1.7	2.657	93
AVERAGE	415.20	65.8	30.4	1.000	3.8	1.037	103
STD DEV	727.43	10.1	11.0	0.158	5.8	1.175	10

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: MO

GROUP	COAL (PPM)	ECOTOM ASH (%)	ECOTOM ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
2	9.00	11.8	0.210	88.2	2.018	0.0	0.000	131
5	2.00	16.3	0.242	20.9	0.966	62.9	5.614	406
9	20.00	.	.	.	.	.	.	.
AVERAGE	10.32	14.0	0.226	54.5	1.452	31.4	2.807	269
STD DEV	9.07	3.2	0.023	47.6	0.744	44.5	3.970	105

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: NA

GROUP	CCAL (PPM)	ECTTOM (%)	ASH (/AL)	TOP (%)	TOP AST (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	677.00	56.1	0.777	42.8	1.712	1.1	0.398	88
2	696.00	55.7	0.637	63.9	1.462	0.3	1.743	115
9	690.00	50.3	0.746	48.5	1.534	0.8	1.235	80
AVERAGE	687.67	47.4	0.720	51.5	1.569	0.8	1.125	94
STD DEV	9.71	10.5	0.073	10.5	0.129	0.4	0.679	18

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
EOILER TYFF:CYCLONE

FLEMENT:NI

GROUP	CCAL (FPM)	ECTTCM (%)	ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
2	16.00	30.2	0.540	69.2	1.586	0.4	1.996	100
5	5.40	22.7	0.338	14.3	0.663	62.9	5.618	131
AVERAGE	10.70	26.6	0.439	41.8	1.125	31.7	3.807	116
STD DEV	7.50	5.2	0.142	38.9	0.652	44.2	2.561	22

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: PB

GROUP	CCAL (PPH)	ECTOM ASH (%)	ECTOM ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	7.40	7.0	0.096	90.7	3.631	2.4	0.835	91
2	4.00	7.5	0.134	89.4	2.045	3.1	15.314	89
5	0.86	7.8	0.116	27.7	1.261	64.5	5.762	95
5	7.40	.	.	.	.	.	.	97
AVERAGE	5.14	7.4	0.116	65.3	2.319	23.3	7.304	93
STD DEV	3.09	0.4	0.019	36.0	1.199	35.7	7.362	4

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

FLEMENT: SB

GROUP	COAL (PPM)	ECTON (%)	ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	1.00	.	.	78.1	1.786	17.5	87.781	.
2	0.50	4.4	0.079	6.2	0.287	77.9	6.955	127
3	0.40	15.9	0.237	.	.	.	.	90
4	1.00	.	.	.	.	.	.	.
AVERAGE	0.72	10.2	0.158	42.1	1.036	47.7	47.368	108
STD DEV	0.32	8.1	0.112	50.8	1.060	42.7	57.152	26

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

FLEMENT: SE

GROUP	CCAL (FFM)	ECOTOM (%)	ASH (/AL)	TOP (%)	ASH (/AL)	VAPOR (%)	CLOSURE (%)
1	3.00	41.0	0.568	33.3	1.335	25.6	76
2	2.20	0.0	0.000	81.8	1.872	18.2	78
5	1.30	2.3	0.034	32.4	1.499	65.3	58
AVERAGE	2.17	14.4	0.201	49.2	1.568	36.4	72
STD DEV	0.85	23.1	0.319	28.3	0.275	25.4	12
						35.319	
						48.270	

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
FOILER TYPE: CYCLONE

ELEMENT: SI

GROUP	COAL (FFM)	ECTOM ASH (%)	ECTOM ASH (/AL)	TCP ASH (%)	TCP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
2	23100.00	57.1	1.019	42.9	0.980	0.0	0.000	99
AVERAGE	23100.00	57.1	1.019	42.9	0.980	0.0	0.000	99
STD DEV								

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: TI

GROUP	COAL (PPH)	ECTOM ASH (%)	TOP ASH (%)	VAPOR (/AL)	CLOSURE (%)
1	550.00	62.2	36.7	1.0	91
2	506.00	43.3	56.2	0.5	105
5	350.00	69.1	23.0	7.9	104
9	710.00	64.0	35.0	1.0	57
AVERAGE	525.00	59.7	37.7	2.6	89
STD DEV	148.07	11.3	13.7	3.5	22

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
EOILER TYPE: CYCLONE

ELEMENT: U

GROUP	CCAL (PPM)	ECTOM ASH (%)	ECTOM ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	2.40	63.5	0.285	35.2	1.407	1.0	0.340	103
2	2.18	35.6	0.640	63.2	1.446	0.9	4.563	108
F	1.50	25.5	0.444	42.5	1.967	27.7	2.469	50
9	1.67	64.0	0.549	35.4	1.110	0.6	0.938	111
AVERAGE	1.94	48.4	0.729	44.1	1.483	7.5	2.077	93
STD DEV	0.42	18.1	0.232	13.2	0.356	13.4	1.884	29

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

ELEMENT: V

GROUP	CCAL (FFM)	ECTOM ASH (%)	ECTOM ASH (/AL)	TOP ASH (%)	TOP ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	37.00	58.8	0.815	35.8	1.554	1.4	0.480	124
2	28.50	40.0	0.712	55.3	1.356	0.8	3.827	130
3	15.00	61.0	0.907	14.1	0.653	24.9	2.225	112
4	21.00	58.8	0.871	40.7	1.276	0.5	0.782	91
AVERAGE	25.38	54.6	0.826	38.5	1.220	6.9	1.829	114
STD DEV	9.52	5.8	0.085	18.6	0.401	12.0	1.535	17

ENRICHMENT IN STREAMS WITH RESPECT TO ALUMINUM
BOILER TYPE: CYCLONE

FLEWMENT: ZN

GROUP	CCAL (PPV)	ECTOM (%)	ASH (/AL)	TOP (%)	ASH (/AL)	VAPOR (%)	VAPOR (/AL)	CLOSURE (%)
1	57.00	3.6	0.050	93.9	3.761	2.5	0.872	65
2	.	7.5	0.133	90.5	2.079	1.6	8.166	103
5	7.80	13.3	0.198	34.1	1.580	52.6	4.696	127
9	85.70	.	.	.	.	.	.	124
AVERAGE	63.27	8.1	0.127	73.0	2.473	18.9	4.578	105
STD DEV	48.41	4.9	0.074	33.7	1.143	29.2	3.649	29